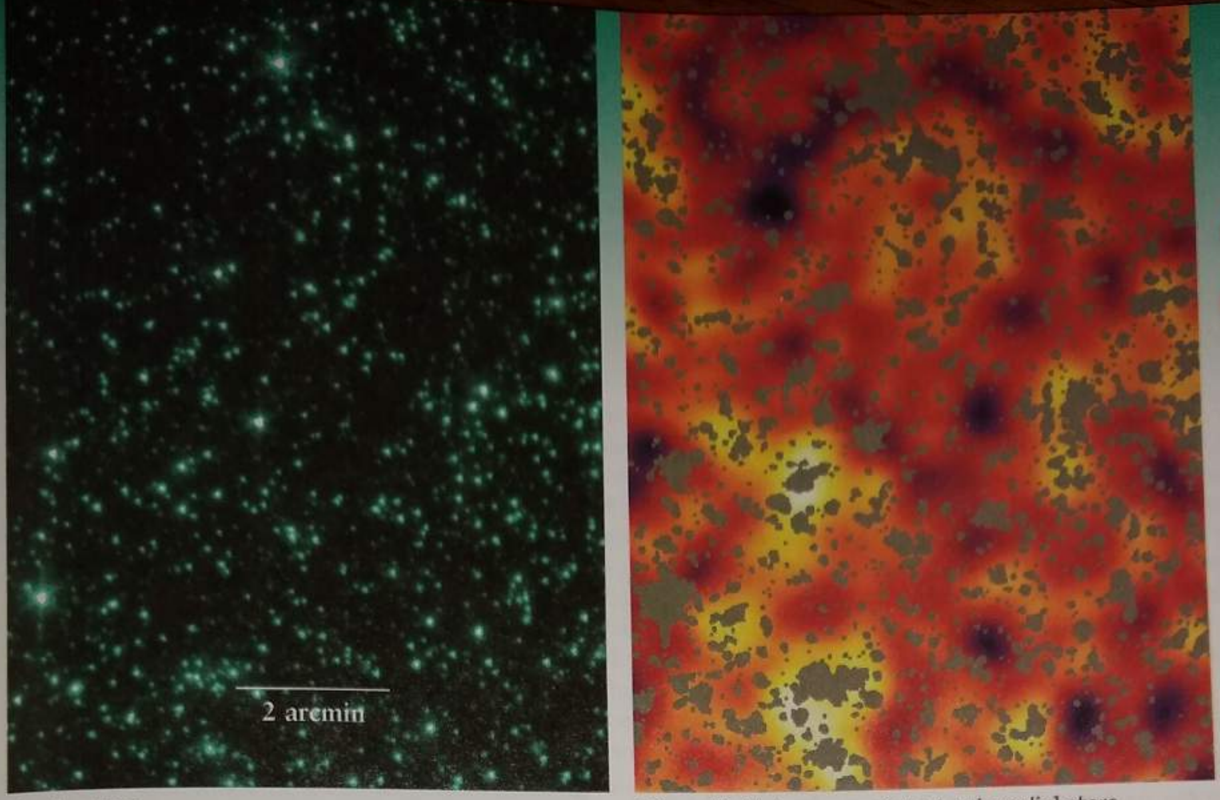


Nearby stars

Infrared light from very distant, primordial stars

These Spitzer Space Telescope images show (left) light from nearby stars and (right) light from a remote population of ancient stars in the same patch of sky with the nearby stars in our Galaxy removed. (NASA; JPL-Caltech; and A. Kashlinsky, Goddard Space Flight Center)

CHAPTER 26

Exploring the Early Universe

LEARNING GOALS

By reading the sections of this chapter, you will learn

26-1 How the fundamental forces of nature and the properties of empty space changed during the first second after the Big Bang

26-2 How the fundamental forces of nature and the properties of empty space changed during the first second after the Big Bang

26-3 How the physics of subatomic particles affected the evolution of the early universe

26-4 As the early universe expanded and cooled, most of the matter and antimatter annihilated each other

26-5 Which chemical elements in today's universe are remnants of the primordial fireball

26-6 How the first stars and galaxies formed in the early universe

26-7 What steps scientists are taking in the quest toward an all-encompassing "theory of everything"

The two images here show a patch of sky near the Big Dipper in the constellation Ursa Major. The left-hand image is dominated by relatively nearby stars in our Galaxy. But when these stars are removed digitally, what remains in the right-hand, false-color image is an intriguing pattern of highly redshifted light from objects much farther away. This radiation is thought to be some of the oldest starlight in the universe: It was emitted by members of the very first generation of stars, born when our universe was less than a billion years old.

Only recently have new telescopes begun to reveal the story of the first stars and first galaxies. But no telescope can ever hope to directly observe events during the first 380,000 years after the Big Bang, when the universe was so opaque that it blocked the free passage of light. We can nonetheless reconstruct some of the events of that hidden epoch, because many aspects of today's universe are relics of the earliest events in the cosmos.

In this chapter we will see evidence that during the first minuscule fraction of a second after the Big Bang, the universe inflated in size by a stupendously large factor of about 10^{50}. During the next 15 minutes, after inflation came to an end, the universe was so dense and hot that particles were constantly colliding at high speeds. As we will see, the events of those 15 violent minutes set the stage for all that came afterward—from the formation of atoms 380,000 years later, to the appearance of the first stars and galaxies some 400 million years after the Big Bang, down to the diverse present-day universe of which we are part.

26-1 The newborn universe underwent a brief period of vigorous expansion

With the discovery of the cosmic microwave background, astronomers had direct evidence that the universe began with a hot Big Bang (see Section 25-4). Remarkably, the microwave background is incredibly uniform, or *isotropic*, across the sky. If we subtract the effects of our own motion through the microwave background (see Figure 25-8), we find that the temperature of the microwave background is the same in all parts of the sky with deviations typically less than 0.01%. These small deviations, or nonuniformities, in the microwave background are also remarkable, in part because their angular sizes help indicate that our universe has a flat geometry (see Section 25-6, especially Figure 25-16). As striking as these observations are, they pose substantial challenges to the standard theory of the expansion of the universe.

The Isotropy Problem: Why Is the Microwave Background So Uniform?

To appreciate why the uniformity of the microwave background poses a problem, think about two opposite parts of the sky, labeled *A* and *B* in Figure 26-1. Both of these points lie on a sphere centered on Earth; our **observable universe** lies within the sphere, and the surface is called our **cosmic light horizon** (see Section 25-3, especially Figure 25-5). We can see light coming from any object on or inside our cosmic light horizon, but we cannot yet see objects beyond this horizon. Even traveling at the speed of light—the ultimate speed limit—no information of any kind from objects beyond our cosmic light horizon has had time to reach us over the entire 13.7-billion-year history of the universe. Thus, the cosmic light horizon defines the limits of our observable universe. (As time passes, our cosmic light horizon expands, so eventually we will receive light from objects that are beyond the present-day horizon.)

Points *A* and *B* in Figure 26-1 lie near the distant edge of the observable universe, just inside our cosmic light horizon, so when we look at these points we are seeing about as far back into the past as possible—that is, the light we see from these points is the cosmic background radiation. In order for the radiation that reaches us from *A* and *B* to be nearly the same, the material of the early universe at *A* must have had the same temperature as at *B*. But for two objects to be at the same temperature, they should have been in contact and able to exchange heat with each other. (A hot cup of coffee and a cold spoonful of cream reach the same temperature only after you pour the cream into the coffee.)

The problem is that the widely separated regions at *A* and *B* have absolutely no connection with each other. As Figure 26-1 shows, point *A* lies outside the cosmic light horizon for point *B*, and point *B* lies outside the cosmic light horizon for point *A*. (Put another way, point *A* lies outside the observable universe of point *B* and vice versa.) Hence, no information has had time to travel between points *A* and *B* over the entire history of the universe. How is it possible, then, that these unrelated parts of the universe have almost exactly the same temperature? This dilemma is called the **isotropy problem** or the **horizon problem**. (*Isotropy* means uniformity *in all directions*.)

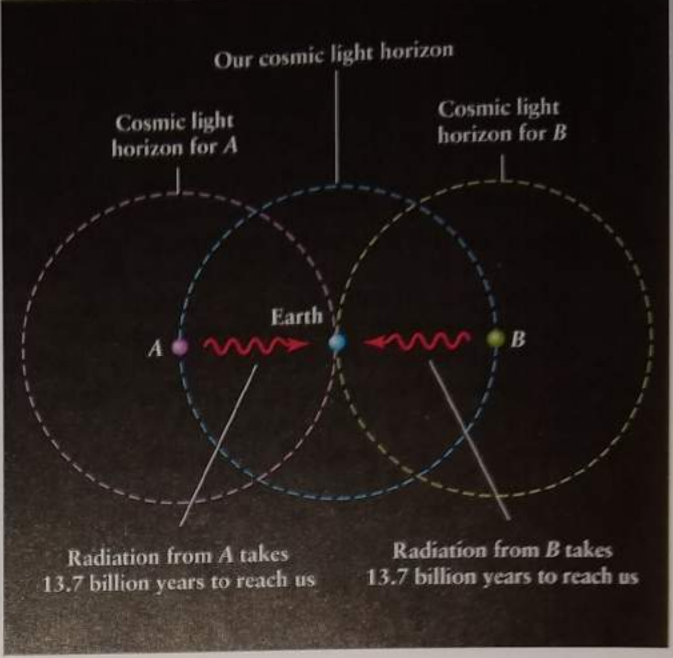


FIGURE 26-1

The Isotropy Problem Regions A and B, both of which lie on our cosmic light horizon, are so far apart that they seem never to have been in communication over the lifetime of the universe. Yet the cosmic background radiation from *A* and *B* and from all other parts of the sky shows that these disconnected regions have almost exactly the same temperature. The dilemma of why this should be is called the isotropy problem.

Even when we consider that the contents of the universe were closer together at earlier times in the universe, the isotropy problem does not go away. While it takes less time for closer regions to come into contact with each other, there is also less time for this to occur because the universe is not as old. When both of these effects are taken into account, there does not seem to be a way for the most distant regions to have reached the same temperature.

The Flatness Problem: Why Is $\Omega_0 = 1$?

The flatness of our universe presents us with a second enigma. Recall that the geometry of our universe depends on the density parameter Ω_0, which is the ratio of the combined average mass density in the universe (ρ_0) to the critical density (ρ_c) (this includes dark energy; see Section 25-6). Observations of temperature variations in the cosmic microwave background indicate that Ω_0 is very close to 1, which corresponds to a flat universe.

For the density parameter Ω_0 to be close to 1 today, it must have been *extremely* close to 1 during the Big Bang. In other words, the density of the early universe was almost exactly equal to the critical density. (The density was much higher than it is today, but the value of the critical density was also much higher. In a flat universe, the average mass density and the critical density decrease together as the universe expands, so that they remain equal at all times.)

The equations for an expanding universe show that any deviation from exact equality would have mushroomed within a fraction of a second. Had the average mass density been slightly less than ρ_c, the universe would have expanded so rapidly that matter could never have clumped together to form galaxies. Without galaxies, there would be no stars or planets, and humans would never have evolved. If, on the other hand, the density had been slightly greater than ρ_c, the universe would soon have become tightly packed with matter. Had this been the case, the gravitational attraction of this matter would long ago have collapsed the entire cosmos in a reversed Big Bang or "Big Crunch," and again humans would never have evolved.

In other words, immediately after the Big Bang the fate of the universe hung in the balance. The tiniest deviation from the precise equality $\rho_0 = \rho_c$ would have rapidly propelled the universe away from the special case of $\Omega_0 = 1$. Had there been such a deviation, we would not be here to contemplate the nature of the universe.

Happily, our universe is one in which galaxies, stars, planets, and humans do exist, a Big Crunch has not taken place, and Ω_0 is very close to 1. These conditions in the universe today tell us that the density of the universe immediately after the Big Bang must have been equal to the critical density to an incredibly high order of precision. In order for space to be as flat as it is today, the value of ρ_0 right after the Big Bang must have been equal to ρ_c to more than 50 decimal places! Unless there was a physical mechanism to bring these two parameters into such close agreement, this extraordinary match is an unappealing characteristic for a scientific theory because it seems to depend on a lucky coincidence.

What could have happened during the first few moments of the universe to ensure that $\rho_0 = \rho_c$ to such an astounding degree of accuracy? Because $\rho_0 = \rho_c$ means that space is flat, this enigma is called the **flatness problem.**

Solving the Problems: The Inflationary Model

In the early 1980s, a remarkable solution was proposed to both the isotropy problem and the flatness problem. Several physicists suggested that the universe might have experienced a brief period of **inflation,** or extremely rapid expansion, shortly after the Planck time. (As we saw in Section 25-3, before the Planck time the normal laws of physics do not properly describe the behavior of space, time, and matter.) During this inflationary epoch, the universe expanded outward in all directions by a factor of about 10^{50}. This epoch of dramatic expansion may have lasted only about 10^{-32} of a second (Figure 26-2).

The inflationary model explains not only why the cosmic microwave background is so uniform, but also how stars, galaxies, and humans can exist

Inflation accounts for the isotropy of the microwave background. During the inflationary epoch, much of the material that was originally near our location was moved out to tremendous distances. Over the past 13.7 billion years, our cosmic light horizon has expanded so that we can see radiation from these distant regions. Hence, when we examine microwaves from opposite parts of the sky, we are seeing radiation from parts of the universe that were originally in intimate contact with one another. This contact allowed for the exchange of heat and is why all parts of the sky have almost exactly the same temperature.

ANALOGY An inflationary epoch can also account for the flatness of the universe. To see why, think about a small portion of Earth's spherical surface, such as a small lake. For all practical purposes, it is impossible to detect Earth's curvature over such a small area, and a small lake looks flat. Similarly, the observable universe is such a tiny fraction of the entire inflated universe that any overall curvature in it is virtually undetectable (Figure 26-3). Like a small lake, the segment of space we can observe looks flat.

Not only does tremendous inflation produce a nearly flat universe, but it does so for just about *any* original degree of curvature prior to inflation. Let us consider why this is very appealing for a scientific theory. Recall that the flatness of our present universe could be explained (in an unsatisfactory way) if, by extraordinary coincidence alone, the value of ρ_0 right after the Big Bang was equal to ρ_c for the first 50 decimal places. Also recall that curvature is determined by ρ_0 (Section 25-6 and Table 25-1), where $\rho_0 = \rho_c$ is flat. Since Figure 26-3 shows that inflation flattens out just about

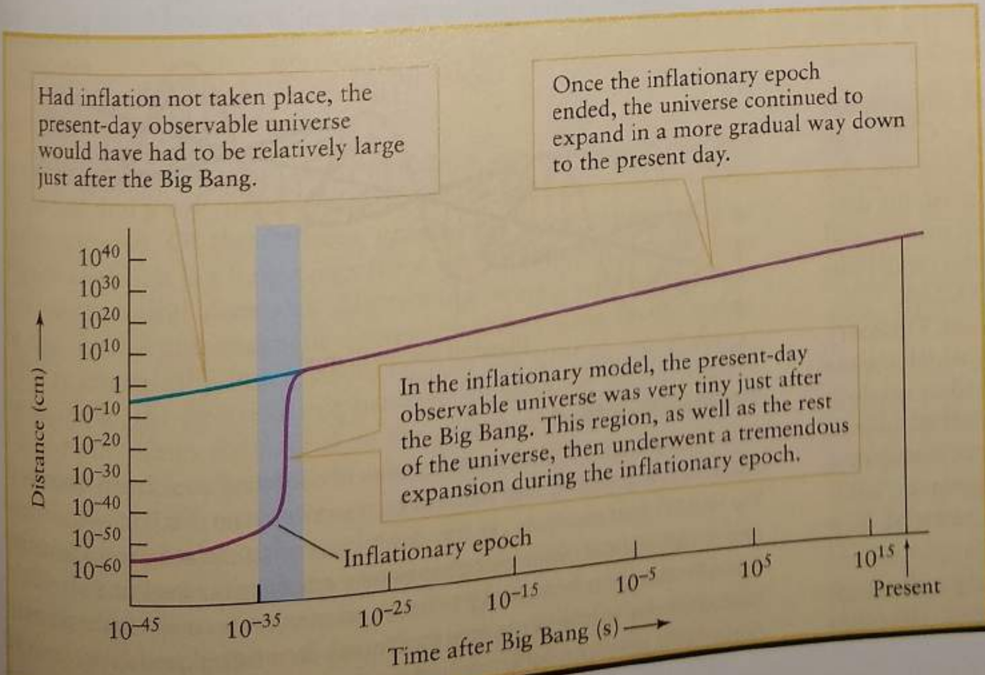


FIGURE 26-2

The Observable Universe With and Without Inflation According to the inflationary model (shown in purple), the universe expanded by a factor of about 10^{50} shortly after the Big Bang. This growth in the size of the present-day observable universe—that portion of the universe that lies within our present cosmic light horizon—occurred during a very brief interval, as indicated by the vertical shaded area on the graph. The blue line shows the projected size of the present-day observable universe soon after the Big Bang if inflation had not taken place. (Adapted from A. Guth)

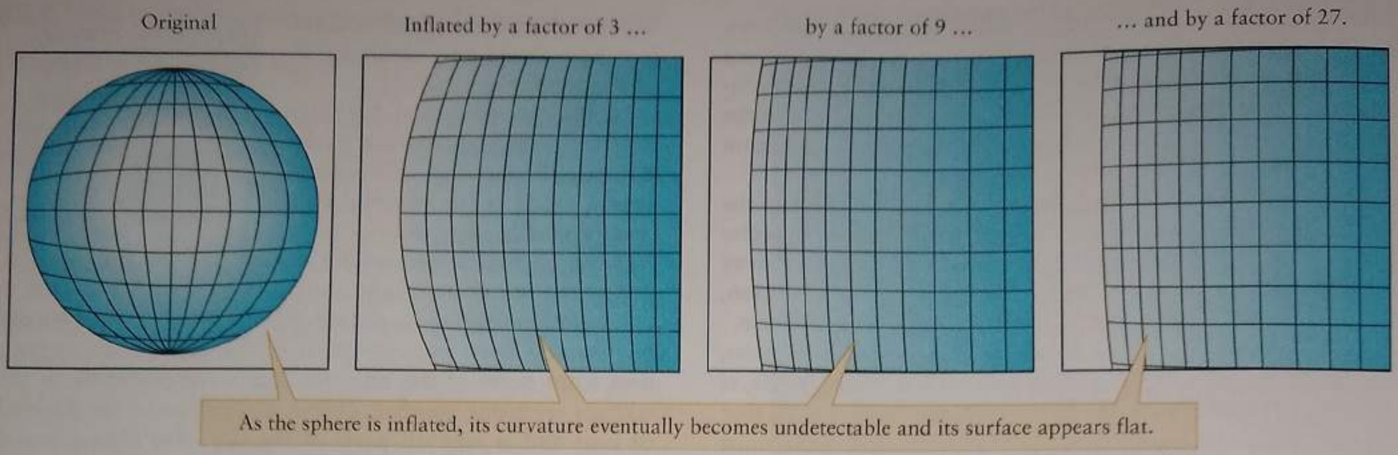


FIGURE 26-3

Inflation Solves the Flatness Problem This sequence of drawings shows how inflation can produce a locally flat geometry. In each successive frame, the sphere is inflated by a factor of 3 (and the number of grid lines on the sphere is increased by the same factor). Note how the curvature of the surface quickly becomes undetectable on the scale of the illustration. Inflation models expand the universe by about a factor 10^{50}, so nearly any original degree of curvature (indicated by the radius of the sphere on the left), will end up nearly flat after inflation. (Adapted from A. Guth and P. Steinhardt)

any original degree of curvature, inflation also *drives any initial value* of ρ_0 toward ρ_c, and removes the need for an unlikely coincidence alone to account for a flat universe.

CAUTION! It is important to note that the concept of inflation does not violate Einstein's law that nothing can travel faster than the speed of light. Remember that the expansion of the universe is the expansion of space itself, not the motion of objects through space. During the inflationary epoch, the distances between particles increased faster than the speed of light, but this was entirely the result of a sudden vigorous *expansion of space*. Particles did not move through space faster than the speed of light; space itself inflated to increase the distance between the particles. Even today, galaxies at redshifts greater than about $z = 1.5$ are receding faster than the speed of light.

Inflation and Polarization of the Cosmic Microwave Background

As we saw in Section 25-8, the detailed properties of temperature fluctuations in the cosmic microwave background, or CMB, can reveal a number of the fundamental parameters that describe our universe. This impressive list includes the Hubble constant, the density parameters for the total energy and for ordinary matter, and also for dark energy. In the near future, even the inflation model can be tested by measuring the *polarization* of light in the CMB.

As illustrated in Figure 26-4, light can be polarized. Ordinary light from a lightbulb or from the Sun is *unpolarized*, which means that the electric fields of many light waves are oriented in random directions. But when light collides with and bounces off an object, it tends to become *polarized*, with its electric fields oriented in a specific direction. In a similar way, the cosmic background radiation acquires a polarization when it scatters from material in a dense cold spot (Figure 26-5).

The effects of inflation are also expected to produce an additional and uniquely polarized CMB signature, although measurem≈ from WMAP (Figure 26-5) were unable to detect these weak signals. However, there are several experiments that hope to detect CMB polarization produced by inflation (these include the *Planck* satellite, BICEP, and POLARBEAR). These are crucial experiments, as inflation is one of the most profound predictions about our early universe, and CMB polarization appears to be our best hope of testing the inflation model.

CONCEPTCHECK 26-1

In Figure 26-1, points *A* and *B* appear too far apart to reach the same temperature by exchanging energy with each other. Nonetheless, distant locations like this in the universe do show nearly the same 2.7 K temperatures. How does the inflation model solve this problem?

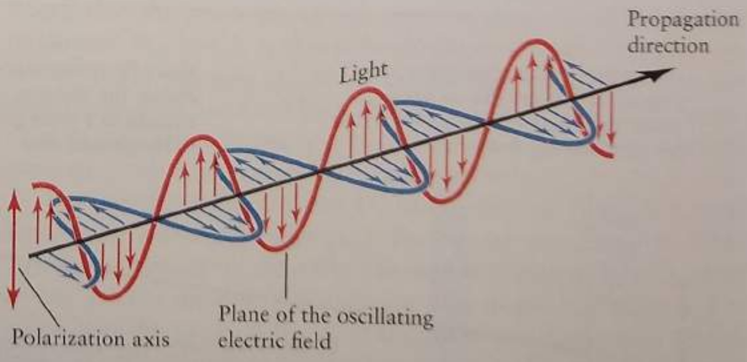


FIGURE 26-4

Polarized Light A light wave consists of oscillating electric and magnetic fields, and the electric field determines the polarization axis. In this illustration, the electric field oscillates up and down in a vertical plane, so the polarization axis is also vertical. Polarized glasses take advantage of the fact that much of the reflective glare from sunlight has its polarizing axis parallel to the ground (perpendicular to the example in this figure). By wearing glasses that block this horizontally polarized light, much of the Sun's glaring reflections are eliminated.

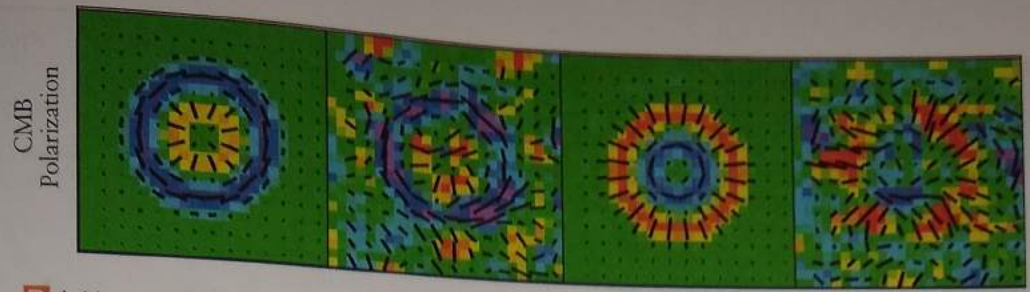


FIGURE 26-5 **R** I V U X G

Polarization of the Cosmic Microwave Background The polarization axes of CMB light are indicated by the orientation of the small black lines. In the two spots on the left, as CMB radiation scatters off of denser regions in the early universe, a unique ring-structured polarization pattern is created. These are the regions that show up as cooler blue spots in images of the CMB temperature fluctuations (such as Figure 25-13). In the two spots on the right, a unique pattern is also created when the CMB scatters off of warmer regions of matter. While these polarization measurements agree with predictions, they are not sensitive enough to test the inflation model, and more sensitive experiments have already begun. (NASA/WMAP Science Team)

CONCEPTCHECK 26-2

Suppose the curvature of the universe before inflation was represented by the surface of a sphere that was 1 billion times smaller than the sphere on the left of Figure 26-3. With this high degree of initial curvature, could inflation have produced a universe that appears nearly flat today?

Answers appear at the end of the chapter.

26-2 Inflation extends the principles that govern the fundamental forces of nature

If the universe went through an episode of extreme inflation, what could have triggered it? Our understanding is that inflation was one of a sequence of remarkable events during the first 10^{-12} seconds after the Big Bang. In each of these events there was a fundamental transformation of the basic physical properties of the universe. To understand what happened during that brief moment of time, when the universe was a hot, dense sea of fast-moving particles and energetic photons colliding with each other, we must first understand how particles interact at very high energies.

The Fundamental Forces of Nature and the Standard Model

Just *four* fundamental forces—*gravitation, electromagnetism,* and the *strong* and *weak forces*—explain the interactions of everything in the universe. Of these forces, gravitation is the most familiar (Figure 26-6a). It is a long-range force that dominates the universe over astronomical distances. Electromagnetism, which accounts for the electric and magnetic forces, creates a long-range force, but it is intrinsically much stronger than the gravitational force. For example, the electric force between an electron and a proton is about 10^{39} times stronger than the gravitational force between those two particles. Because the electromagnetic force is stronger by a factor of 10^{39}, electromagnetism, not the gravitation, holds electrons in orbit about the nuclei in atoms.

We do not generally observe longer-range effects of the electromagnetic force, because there is usually a negative electric charge for every positive charge and a south magnetic pole for every north magnetic pole. Thus, over great volumes of space the effects of electromagnetism effectively cancel out. No similar canceling occurs with gravity because there is no equivalent "negative mass." Because the effects of gravity do not cancel out, the force that holds Earth in orbit around the Sun is gravitational, not electromagnetic.

The **strong force** holds protons and neutrons together to form the nuclei of atoms (Figure 26-6b). It is said to be a *short-range force:* Its influence extends only over distances less than about 10^{-15} m, about the diameter of a proton. Without the strong force, nuclei would disintegrate because of the electric repulsion of the positively charged protons. In fact, the strong force overpowers the electric forces inside nuclei. While there are technical differences, the strong force is also referred to as the **nuclear force.**

The weak force, which also is a short-range force, is at work in certain kinds of radioactive decay (Figure 26-6c). An example is the transformation of a neutron (n) into a proton (p), in which an electron (e^-) is released along with a nearly massless particle called an antineutrino ($\overline{\nu}$):

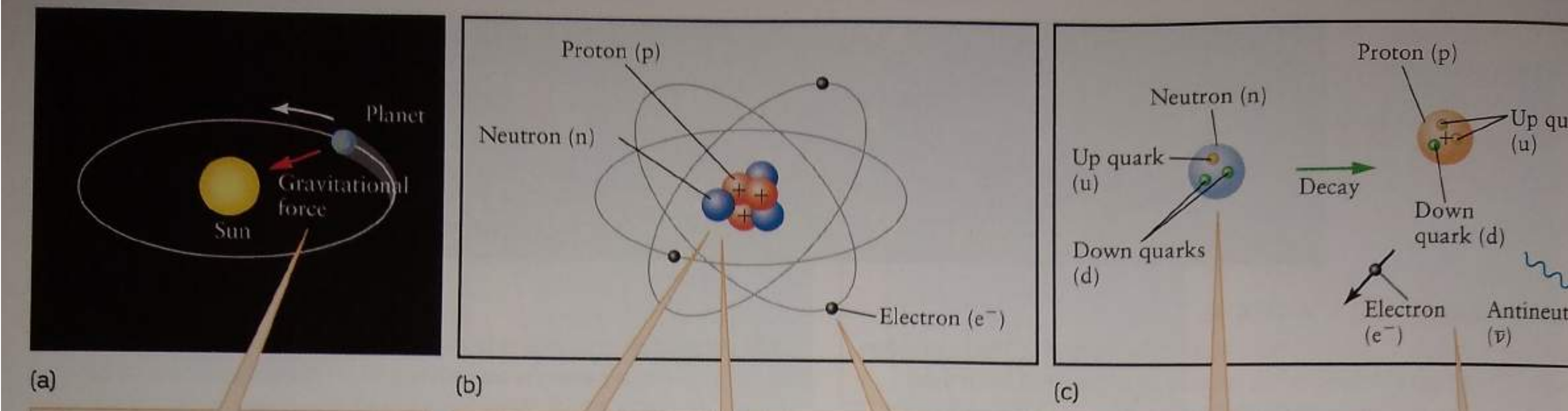
$$n \rightarrow p + e^- + \overline{\nu}$$

Numerous experiments in nuclear physics demonstrate that protons and neutrons are themselves composed of even more basic particles called **quarks,** the most common varieties being "up" (u) quarks and "down" (d) quarks. A proton is composed of two up quarks and one down quark, a neutron of two down quarks and one up quark.

In the 1970s the concept of quarks led to a breakthrough in our understanding of the strong and weak forces. The strong force holds quarks together, while the weak force is at work whenever a quark changes from one variety to another. For example, when a neutron decays into a proton, one of the neutron's down quark changes into an up quark, as shown in Figure 26-6c. Thus, the weak force is responsible for transformations such as

$$d \rightarrow u + e^- + \overline{\nu}$$

In the 1940s, physicists Richard P. Feynman and Julian S Schwinger (working independently in the United States) and Sir Itiro Tomonaga (in Japan) succeeded in developing a basic description of what we mean by force. Focusing their attention on the electromagnetic force, they tried to describe exactly what happen when two charged particles interact. According to their theor now called **quantum electrodynamics,** charged particles intera



The gravitational force is too weak to be important on the subatomic scale. It is *the* most important force on astronomical scales, since stars and planets have no net electric charge and the strong and weak forces do not operate over long distances.

The strong force binds protons and neutrons together to form nuclei.

The electromagnetic force attracts electrons and nuclei, forming atoms.

The electromagnetic force by itself makes protons repel, but this is overwhelmed by attraction due to the strong force.

Another aspect of the strong force binds quarks together to form protons and neutrons.

The weak force causes an isolated neutron to deca into a proton, an electron, and an antineutrino. T involves a down quark changing into an up quark

Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	1/137	photons	charged particles	infinite	holding atoms toget
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

The Standard Model of the Elementary Particles

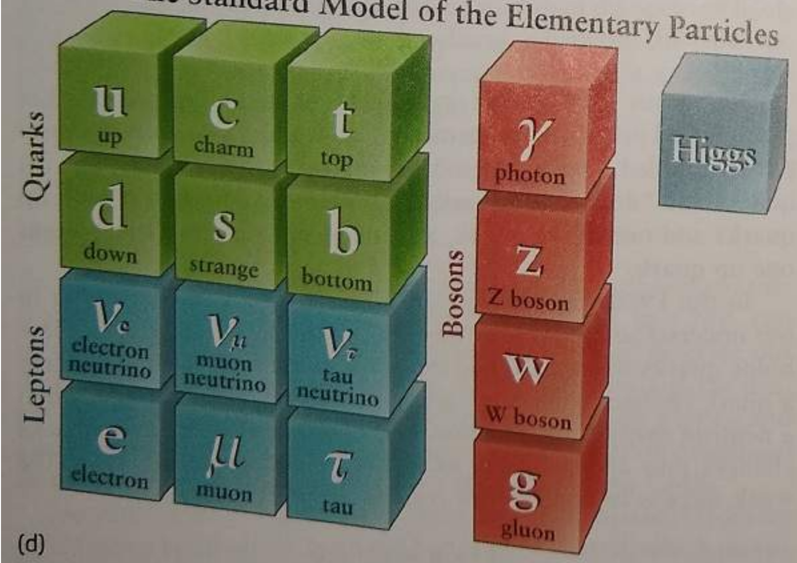


FIGURE 26-6

The Four Forces and the Standard Model **(a)** Gravitation is domin on the scales of planets, star systems, and galaxies, while **(b), (c)** the stror electromagnetic, and weak forces hold sway on the scale of atoms and nu **(d)** The Standard Model describes the particles involved in the electromagi weak, and strong forces. Bosons transmit the different forces; the photon transmits the electromagnetic force between charged particles (holding electrons in atoms); the gluon transmits the force between quarks (holding together atomic nuclei); and the intermediate vector bosons (Z,W) transmit weak force (resulting in certain radioactive decays). These are all the know fundamental particles found in nature.

by exchanging *virtual* photons that cannot be directly observed. (These virtual photons will be explored further in Section 26-3.)

Quantum electrodynamics has proved the most successful theory in modern physics. It describes with remarkable accuracy many details of electromagnetic forces and interactions between charged particles. Inspired by these successes, physicists developed similar theories for the other three forces. A key feature of a microscopic description of force is that two particles exert a force on each other by exchanging a third and different particle (Figure 2(For example, the weak force occurs when particles exchange ticles called **intermediate vector bosons**, and quarks stick toge by exchanging elementary particles called **gluons**. These the

Experimental and theoretical research into t basic forces of nature hel us understand the evolutio of the cosmos

FIGURE 26-7

Forces Due to Particle Exchange Imagine each skateboarder as a particle that can move freely. By tossing a basketball, the right skateboarder is pushed backward, and by catching the ball, the left skateboarder is pushed away as well. This example of particle exchange illustrates a repulsive force, and in quantum physics, particle exchange can produce both repulsive and attractive forces.

have been verified by experiments, and our overall understanding of the known particles is called the Standard Model (Figure 26-6d). The table in Figure 26-6 summarizes these features of the four fundamental forces.

CONCEPTCHECK 26-3

A neutron consists of one up quark (u) and two down quarks (d) as in Figure 26-6c. Are there any other particles in the Standard Model that you would expect to be involved in holding a neutron together?

Answer appears at the end of the chapter.

Experimentally Verified Unification Theories and the Higgs Particle

Physicists made important progress in understanding the weak force during the 1970s. Steven Weinberg, Sheldon Glashow, and Abdus Salam proposed a theory with three types of intermediate vector bosons, which are exchanged in various manifestations of the weak force. These three particles were actually discovered in experiments in the 1980s, providing strong support for the theory.

A startling prediction of the Weinberg-Glashow-Salam theory is that the weak force and the electromagnetic force should be identical to each other for particles with energies greater than 100 GeV. (One GeV equals 10^9, or 1 billion, electron volts; see Section 5-5.) In other words, if particles are slammed together with a total energy greater than 100 GeV, then electromagnetic interactions become indistinguishable from weak interactions. We say that above 100 GeV the electromagnetic force and the weak force are "unified" into a single **electroweak force.** This is our first example of the "unification" of forces, and the only one to be experimentally verified.

This unification occurs because the three types of intermediate vector bosons behave just like photons above 100 GeV. At such high energies, these three particles actually lose their mass, and the weak force becomes a long-range force with the same intrinsic strength as electromagnetism. Physicists describe this similarity by saying that "symmetry is restored" above 100 GeV.

In the world around us, however, the typical energies with which particles interact are much lower, on the order of 1 eV or less. Below 100 GeV, intermediate vector bosons behave like massive particles, but photons have no mass. Because intermediate vector bosons and photons are not similar at low energies, we say that "symmetry is broken" below 100 GeV, which is why the electromagnetic and the weak forces behave so differently in the lower-energy world around us. In the language of physics, the electroweak force experiences a **spontaneous symmetry breaking;** above 100 GeV the electroweak force represents a form of symmetry, and below 100 GeV, the symmetry is broken and two distinct forces emerge: the electromagnetic and weak forces.

ANALOGY As abstract as spontaneous symmetry breaking sounds, it is a familiar phenomenon when describing water. At room temperature, water is liquid. If you were to take a vantage point from within liquid water, it would look the same in all directions. In this sense, liquid water is uniform and symmetric. At lower temperatures, however, water freezes into ice crystals and no longer appears the same in every direction (Figure 26-8). While commonly referred to as a "phase transition," this change can also be described as the spontaneous symmetry breaking of water when it freezes.

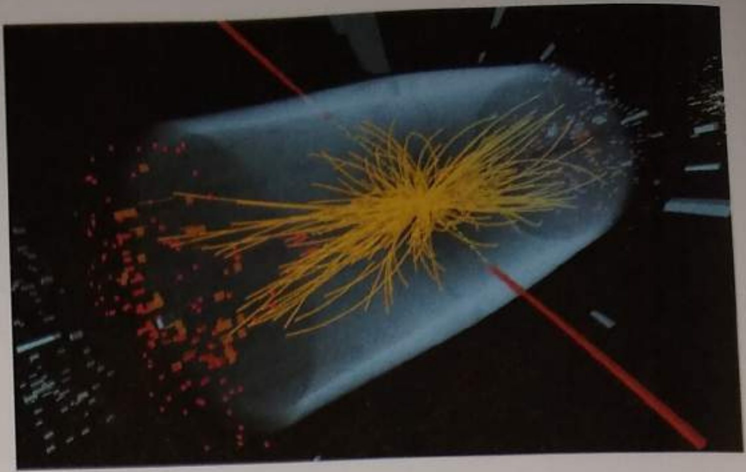
FIGURE 26-8 R I V U X G

Spontaneous Symmetry Breaking of Water When liquid water freezes it transitions from a highly uniform and symmetric state to ice crystals that break this uniformity. Since lower temperatures correspond to lower average energy for the water's particles, we say that water experiences a spontaneous symmetry breaking at lower energy. By analogy, the high temperature symmetric water is like the electroweak force, and the ice crystals are like the electromagnetic and weak forces. (Frank Siteman/Aflo Relax/Corbis)

(a)

(b)

As strange as these ideas sound, they have been tested to great precision in particle accelerators that smash particles together at extremely high energies. The world's largest particle accelerator is CERN in Europe (Figure 26-9), which made a monumental discovery in 2012. For more than 40 years, there was one major prediction of the Standard Model that had not been observed—the Higgs particle (see Figure 26-6d). This key particle was predicted as part of the electroweak symmetry breaking that gives the Standard Model some of the properties we observe. In fact, one of these properties is mass: The Higgs particle "gives mass" to the other particles (except for the massless photons and gluons) by interacting with them. Since you and I, the planets, and the stars are all made of these particles, we owe our heft to the Higgs particle.



(c)

FIGURE 26-9 R I V U X G

Discovery of the Higgs Particle **(a)** The CERN particle collider is 27 km in diameter and straddles the border between Switzerland and France. Protons are accelerated to speeds very close to the speed of light in a tube (shown in red) that is around 100 m below ground. **(b)** When these protons collide, their energy produces numerous additional particles that are tracked and detected in enormous particle detectors as shown here (under construction). This is a direct result of converting energy to mass via $E = mc^2$. **(c)** By analyzing the particle tracks (in yellow), the mass, charge, and various other properties of the particles can be determined. This is how new particles are discovered, including the Higgs particle. (a, b: © 2001 CERN; c: HANDOUT/AFP/Getty Images/Newscom)

[illegible] How does the Higgs particle give other particles mass? First of all, in the realm of quantum physics, every particle is associated with an extended entity called a "field." Thus, the Higgs particle is associated with a Higgs field, and this field is present even at low energy when the Higgs particle itself is absent. To acquire the property of mass, particles in the Standard Model interact with this Higgs field, which produces a force on them. This force is somewhat similar to what a crumb experiences when it's surrounded by syrup; analogously, the Higgs field is like a syrup that pervades all of space. The interactions of particles with this "syrup" make it harder to set particles into motion, giving them a property of mass. (Interestingly, it i not known why different particles interact more strongly to hav different masses; this is an unsolved problem in physics.)

Long before the Higgs particle was observed, the Standar Model's overall success at unifying the electromagnetic force wit the weak force led to attempts at unifying the remaining tw forces: the strong force and gravity.

CONCEPTCHECK 26-4

Are the photons, the W and the Z bosons of the Standard Model in Figure 26-6d, "symmetric," meaning that they all ha the same physical properties?

CONCEPTCHECK 26-5

Symmetry breaking, which refers to the fact that below 100 GeV, the electroweak force appears as two distinct forces (electromagnetic and weak) is said to be "spontaneous." What is spontaneous about symmetry breaking?

Answers appear at the end of the chapter.

Proposed Unification Theories of all the Forces

In the 1970s, several physicists proposed **grand unified theories** (or GUTs), which predict that the strong force becomes unified with the weak and electromagnetic forces (but not gravity) at energies above 10^{14} GeV. In other words, if particles were to collide at energies greater than 10^{14} GeV, the strong, weak, and electromagnetic interactions would all be long-range forces and would be indistinguishable from each other.

Many physicists suspect that all four forces, including gravitation, may be unified at energies greater than 10^{19} GeV (Figure 26-10). That is, if particles were to collide at these colossal energies, there would be no difference between the gravitational, electromagnetic, and nuclear forces. However, no one has yet succeeded in working out the details of such a **supergrand unified theory,** which is sometimes called a **theory of everything** (or TOE). The favored TOE to describe all of the forces is called string theory, which we will discuss further in Section 26-7.

A supergrand unified theory or TOE that includes gravitation would also be a theory of *quantum gravity* (which would describe the effects of strong gravity on microscopic scales). We have already seen with black holes and the Big Bang that developing the answers to some questions requires a theory of quantum gravity (such as what happens to the information about material after it falls into a black hole). Similar to the particle exchange mechanism between the other forces, in a quantum gravity theory the gravitational force is predicted to arise when particles exchange **gravitons,** although gravitons themselves have not been observed.

The Fundamental Forces in the Early Universe

Figure 26-10 shows how the various forces are thought to have changed during the first fraction of a second after the Big Bang. Before the Planck time (from $t = 0$ second to $t = 10^{-43}$ second), particles collided with energies greater than 10^{19} GeV, and all four forces were unified. Because we do not yet have a TOE that properly describes the behavior of gravity, we remain ignorant of what was going on during the first 10^{-43} second of the universe's existence. We know, however, that by the end of the Planck time, the expansion and cooling of the universe had caused the energy of particles to fall to 10^{19} GeV. At energies below this level, gravity is not unified with the other three forces.

In the language of physics, at $t = 10^{-43}$ second there was a spontaneous symmetry breaking in which gravity was "frozen out" of the otherwise unified hot soup that filled all space. In such a "soup," the typical energy of a particle (E) is related to temperature (T) by $E = kT$, where k is the Boltzmann constant (about 10^{-4} eV/K, or 10^{-13} GeV/K). Thus, the temperature of the universe was 10^{32} K when gravity emerged as a separate force.

As the universe expanded, its temperature decreased and the energy of particles decreased as well. (We discussed this property of gases in Box 19-1.) At $t = 10^{-35}$ second, the energy of particles in the universe had fallen to 10^{14} GeV, equivalent to a temperature of 10^{27} K. Below these energies and temperatures, the strong force is no longer unified with the electromagnetic and weak forces. Thus, at $t = 10^{-35}$ second, there was a second spontaneous symmetry breaking, at which time the strong force "froze out."

The inflationary epoch is thought to have begun at this point. Physicists hypothesize that before the strong force decoupled from the electroweak force, the universe was in an unstable state called a **false vacuum.** In this state, physicists hypothesize that the energy associated with a quantity called the *inflaton field* (or inflation field) had a nonzero value (Figure 26-11a). (Just as the space around a magnet is permeated by a magnetic field, like that shown in Figure 7-13a, the entire universe is thought to be permeated by

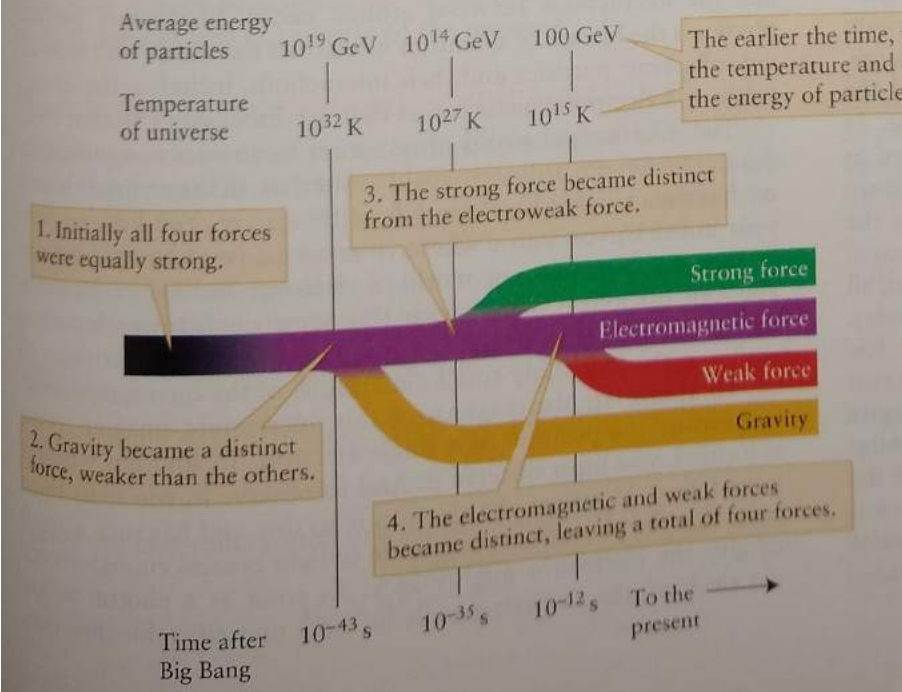


FIGURE 26-10

Unification of the Four Forces The strength of the four fundamental forces depends on the energy of the particles that interact. As shown in this schematic diagram, the higher the energy, the more the forces resemble each other. Also included here are the temperature of the universe and the time after the Big Bang when the strengths of the forces are thought to have been equal. At energies between 10^{14} and 10^{19} GeV, the forces might be described by a grand unified theory (GUT), and at energies above 10^{19} GeV, the forces migh all appear similar in a supergrand unified theory.

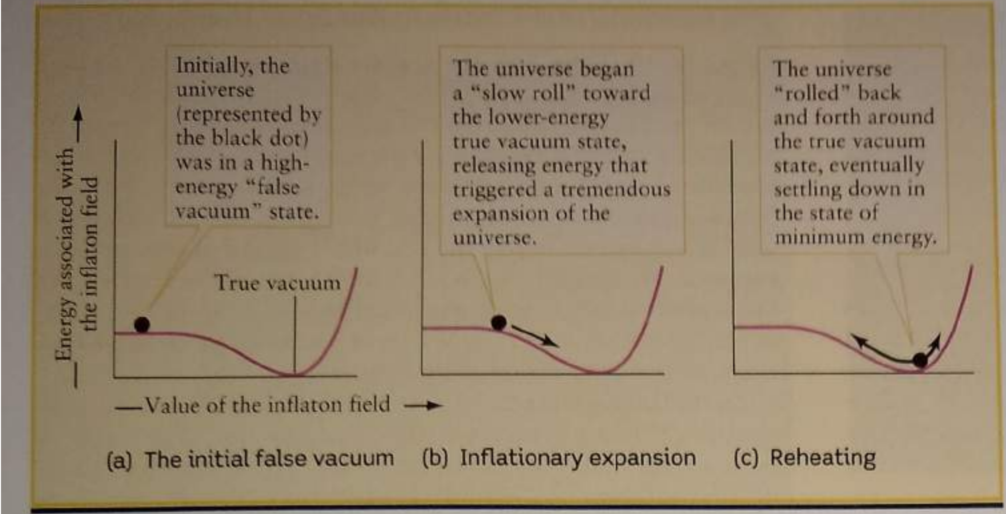


FIGURE 26-11

Inflation: Transitioning from the False Vacuum to the True Vacuum **(a)** The energy of the vacuum is thought to be determined by the value of a quantity called the inflaton field. As shown by the red curve in this diagram, this energy is at a minimum for a certain value of this field. The state of lowest energy is called the true vacuum. **(b)** Inflation is associated with the universe making a transition from its initial false-vacuum state to a true-vacuum state. This expansion took place over a period of about 10^{-32} seconds, during which the universe cooled to a temperature of about 3 K. **(c)** As the universe "settled in" to the true vacuum state, energy was released that reheated the universe to a temperature of 10^{27} K.

the inflaton field.) This state was unstable in the same sense as a ball perched atop a cone with a pointed top: The ball will stay there if left undisturbed, but will roll downhill if even slightly disturbed. In an analogous way, it is thought that at the time that the strong and electroweak forces decoupled, the universe "rolled downhill" to the *true vacuum,* a state of lower energy. The universe's transition to the true vacuum released energy that caused it to expand tremendously in a brief interval of time (Figure 26-11b). By the time the inflationary epoch had ended, about 10^{-32} second after the Big Bang, the universe had increased in scale by a factor of roughly 10^{50}.

The rapid expansion of the universe also gave rise to a rapid cooling. At the end of the inflationary epoch, the temperature of the universe may have dropped to about 3 K, about the same as the temperature that the cosmic background radiation has today. But as the universe finally settled into the vacuum-energy state, an additional amount of energy was released that went into *reheating* the universe to a temperature of 10^{27} K—about the same as it had before inflation began (Figure 26-11c). Thus, inflation caused the universe to expand tremendously while having no net effect on its temperature.

After the end of the inflationary epoch at $t = 10^{-32}$ second, the universe continued to expand and cool at a more sedate rate. At $t = 10^{-12}$ second, the temperature of the universe had dropped to 10^{15} K, the energy of the particles had fallen to 100 GeV, and there was a final spontaneous symmetry breaking as described by the Standard Model. That last symmetry breaking separated the electromagnetic force from the weak force, and from that moment on, all four forces have interacted with particles essentially as they do today.

The electroweak symmetry breaking around 100 GeV has been verified, including the predicted Higgs particle. While the two symmetry breaking events predicted to occur at higher energies (and earlier times) have not been observed, they follow a similar mechanism for what has been observed at lower energies with the electroweak force. This lower-energy success certainly does not prove that these higher energy theories are correct, but it provides motivation for formulating and testing them.

26-3 During inflation, all the mass and energy in the universe burst forth from the vacuum of space

If the ideas of inflation are correct, it was a brief but stupen dous expansion of the universe soon after the beginning of time Physicists now realize that inflation helps explain where all th matter and radiation in the universe came from. To see how violent expansion of space could create particles, we must firs understand what quantum mechanics tells us about space.

Quantum Mechanics and the Heisenberg Uncertainty Principle

Quantum mechanics is the branch of physics that explains th behavior of nature on the atomic scale and smaller. For exampl quantum mechanics tells us how to calculate the structure of atom and the interactions between atomic nuclei. **Elementary partic physics** is the branch of quantum mechanics that deals with indivi ual subatomic particles and their interactions, including the stron weak, and electromagnetic forces that we discussed in Section 26-

The microscopic world of quantum mechanics is significant different from the ordinary world around us. In the ordinary wor we have no trouble knowing where things are. You know whe your house is; you know where your car is; you know where th book is. In the subatomic world of electrons and nuclei, howev you can no longer speak with this same confidence. A certa amount of fuzziness, or uncertainty, enters into the description reality at the incredibly small dimensions of the quantum world

To appreciate the reasons for this uncertainty, imagine tryi to measure the position of a single electron. To find out where is located, you must observe it. And to observe it, you must shi a light on it. However, the electron is so tiny and has such a sma mass that the photons in your beam of light possess enough ener to give the electron a mighty kick. As soon as a photon strik the electron, the electron recoils in some unpredictable directio onsequently, no matter how carefully you try to measure the recise location of an electron, you necessarily introduce some ncertainty into the speed of that electron.

These ideas are at the heart of the **Heisenberg uncertainty rinciple,** first formulated in 1927 by the German physicist Werner leisenberg, one of the founders of quantum mechanics. This principle states that there is a reciprocal uncertainty between position nd momentum (momentum is equal to the mass of a particle mulplied by its velocity). The more precisely you try to measure the osition of a particle, the more unsure you become of how the particle is moving. Conversely, the more accurately you determine the omentum of a particle, the less sure you are of its location. These estrictions are not a result of errors in making measurements; they re fundamental limitations inherent to all natural phenomena.

There is an analogous uncertainty involving energy and time. ou cannot know the energy of a system with infinite precision at very moment in time. Over short time intervals, there can be great ncertainty about the amounts of energy in a subatomic system. pecifically, let ΔE be the smallest possible uncertainty in energy neasured over a short interval of time Δt. (Astronomers and hysicists often use the capital Greek letter delta, Δ, as a prefix to lenote a small quantity or a small change in a quantity.)

eisenberg uncertainty principle for energy and time

$$\Delta E \times \Delta t = \frac{h}{2\pi}$$

ΔE = uncertainty in energy

Δt = time interval over which energy is measured

h = Planck's constant = 6.625×10^{-34} J s

This equation says that the shorter the time interval Δt, the greater the energy uncertainty ΔE must be in order to ensure that the product of ΔE and Δt is equal to $h/2\pi$.

We might look upon the Heisenberg uncertainty principle as merely an unfortunate limitation on our ability to know everything with infinite precision. But, in fact, this principle provides startling insights into the nature of the universe.

Spontaneously Created Matter and Antimatter

We have seen that one of the important conclusions of Einstein's special theory of relativity is the equivalence of mass and energy: $E = mc^2$ (see Section 16-1). There is nothing uncertain about the speed of light (c), which is an absolute constant. Therefore, any uncertainty in the energy of a physical system can be attributed to an uncertainty Δm in the mass. Thus,

$$\Delta E = \Delta m \times c^2$$

Combining this expression with the previous equation, we obtain

Heisenberg uncertainty principle for mass and time

$$\Delta m \times \Delta t = \frac{h}{2\pi c^2}$$

Δm = uncertainty in mass

Δt = time interval over which mass is measured

h = Planck's constant = 6.625×10^{-34} J s

c = speed of light = 3.00×10^8 m/s

This result is astonishing. It means that over a very brief interval Δt of time, we cannot be sure how much matter there is in a particular location, even in "empty space." During this brief moment, matter can spontaneously appear and then disappear. The greater the amount of matter (Δm) that appears spontaneously, the shorter the time interval (Δt) during which it can exist before disappearing into nothingness. This bizarre state of affairs is a natural consequence of quantum mechanics.

No particle can appear spontaneously by itself, however. For each particle created, so is a second, almost identical **antiparticle;** particles are made of matter, and antiparticles are made of antimatter. In other words, equal amounts of matter and **antimatter** come into existence and then disappear. (These are the virtual particle pairs discussed in Section 25-7, and in more depth below.)

Quantum mechanics reveals that "empty" space is not empty, but is seething with particles and antiparticles that appear and then annihilate

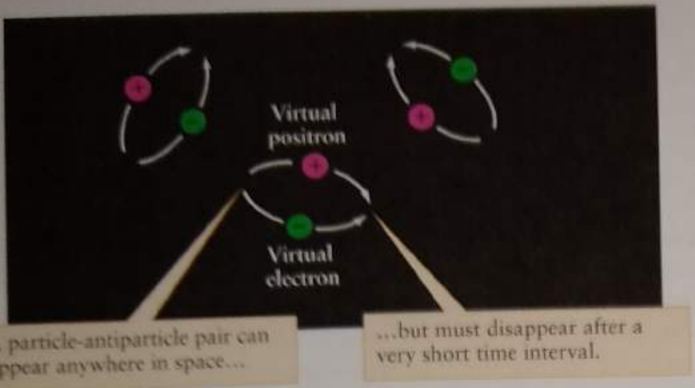
Despite its exotic name, there is actually nothing terribly mysterious about antimatter. A particle and an antiparticle are identical in almost every respect; their main distinction is that they carry opposite electric charges. For example, an ordinary electron (e^-) carries a negative charge; the corresponding antiparticle has the same mass but a positive charge, which is why it is called a **positron** (e^+, and also called an antielectron). Protons (with positive charge) also have an antimatter partner called an **antiproton** (with negative charge). Particles that have no electric charge can also have corresponding antiparticles. An example is the neutrino (ν); we met its antiparticle, the antineutrino ($\bar{\nu}$), in Section 26-2. The antineutrino is also electrically neutral, but differs from the neutrino in having opposite values of other, more subtle physical properties.

A spontaneously created particle-antiparticle pair lasts for only an incredibly brief time. For example, consider an electron and a positron, each with a mass of 9.11×10^{-31} kg. If we rewrite the Heisenberg uncertainty principle for mass and time to solve for Δt and then substitute the combined mass of $2 \times 9.11 \times 10^{-31}$ kg, we find that a spontaneously created electron-positron pair can last for a time

$$\Delta t = \frac{1}{\Delta m}\,\frac{h}{2\pi c^2} = \frac{1}{2 \times 9.11 \times 10^{-31}} \times \frac{6.625 \times 10^{-34}}{2\pi(3.00 \times 10^8)^2}$$

$$= 6.43 \times 10^{-22}\ \mathrm{s}$$

In other words, an electron and a positron can spontaneously appear and then disappear without violating any laws of physics—but they can remain in existence for no longer than 6.43×10^{-22} second. In fact, the laws of quantum physics *require* that electrons and positrons constantly pop in and out of existence. The same behavior applies to all massive particles, but the more massive the



A particle-antiparticle pair can appear anywhere in space...

...but must disappear after a very short time interval.

FIGURE 26-12

Virtual Pairs Pairs of particles and antiparticles can appear and then disappear anywhere in space provided that each pair exists only for a very short time interval, as dictated by the uncertainty principle. In this sketch, electrons are shown in green and positrons are shown in red.

particle, the shorter the time interval it can exist. Next, we look at this process in more detail.

Virtual Pairs

Spontaneous creation can and does happen absolutely anywhere and at any time, not just under the unusual conditions of the early universe. (It is happening right now in the space between this book and your eyes.) Quantum mechanics tells us that if a process is not strictly forbidden, then it must occur. Pairs of every conceivable particle and antiparticle are constantly being created and destroyed at every location across the universe. However, we have no way of observing these pairs directly without violating the uncertainty principle. For this reason, they are called virtual pairs. They do not "really" exist in the same sense as ordinary particles; they "virtually" exist. The particles that are exchanged in the four fundamental forces (see Section 26-2) are also virtual particles.

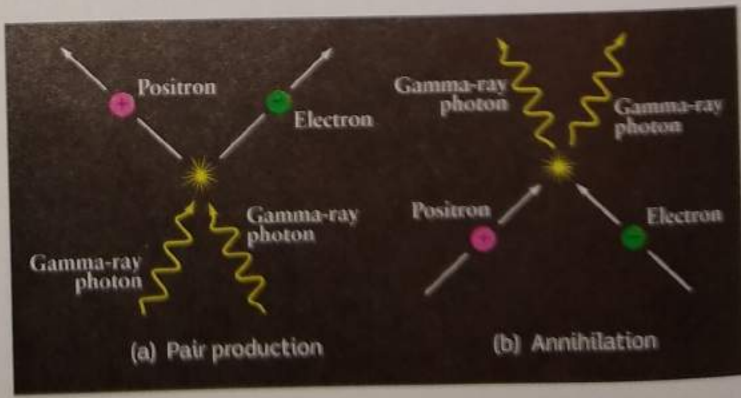
Although virtual pairs of particles and antiparticles cannot be observed directly, their effects have nonetheless been detected. Imagine, for example, an electron in orbit about the nucleus of an atom, such as a hydrogen atom. Ideally, the electron should follow its orbit in a smooth, unhampered fashion. However, because of the constant brief appearance and disappearance of pairs of particles and antiparticles, minuscule electric fields exist for extremely short intervals of time. These tiny, fleeting electric fields cause the electron to jiggle slightly in its orbit. This jiggling produces slight changes in the energies of different electron orbits in the hydrogen atom, which manifest themselves as a minuscule shift in the wavelengths of the hydrogen spectral lines. (We discussed the connection between the energies of electron orbits in hydrogen and the hydrogen spectrum in Section 5-8.)

This shift was first detected in 1947 and today is known as the **Lamb shift.** The Lamb shift and more recent experiments provide powerful evidence that every point in space, all across the universe, is seething with virtual pairs of particles and antiparticles. In this sense, "empty space" is actually not empty at all. Figure 26-12 sketches the constant appearance and disappearance of virtual particles and antiparticles.

Pair production is routinely observed in high-energy particle accelerators. Indeed, it is one of the ways in which physicists manufacture exotic species of particles and antiparticles. The only requirement is that nature's balance sheet be satisfied. To create a particle and an antiparticle having a total mass M, the incoming gamma-ray photons must possess an amount of energy E that is greater than or equal to Mc^2. If the photons carry too little energy (less than Mc^2), pair production will not occur. Likewise, the more energetic the photons, the more massive the particles and antiparticles that can be manufactured.

Not all pairs of particles and antiparticles are virtual. In a phenomenon called **pair production,** pairs of highly energetic gamma rays (photons) can convert their energy into pairs of particles and antiparticles (Figure 26-13a). Quite simply, the gamma-ray photons disappear upon colliding into each other and convert their energy into a particle and an antiparticle. As real particles, they are directly observable and do not have to annihilate. While Figure 26-13a shows this process of pair production, Figure 26-13b shows the inverse process of **annihilation,** in which a particle and antiparticle collide with each other and are converted into high-energy gamma rays.

Around 1980, physicists began applying these ideas to their thinking about the creation of the universe. During the inflationary epoch, space was expanding with explosive vigor. As we have seen, however, all space is seething with virtual pairs of particles and antiparticles. Normally, a particle and an antiparticle have no trouble getting back together in a time interval (Δt) short enough to be in compliance with the uncertainty principle. During inflation, however, the universe expanded so fast that particles were rapidly separated from their corresponding antiparticles. Deprived of the opportunity to recombine and annihilate, these virtual particles became *real* particles in the real world. In this way, the universe was flooded with particles and antiparticles created by the violent expansion of space (Figure 26-14). For a "report card" on cosmology theories, including inflation, see the article at the end of this chapter.



(a) Pair production

(b) Annihilation

FIGURE 26-13

Pair Production and Annihilation (a) Pairs of virtual particles can be converted into real particles by high-energy gamma-ray photons. In this illustration, an electron (shown in green) and a positron (in red) are produced. This process can take place only if the combined energy of the two photons is no less than Mc^2, where M is the total mass of the electron and positron. (b) Conversely, a particle and an antiparticle can annihilate each other and be transformed into energy in the form of gamma rays.

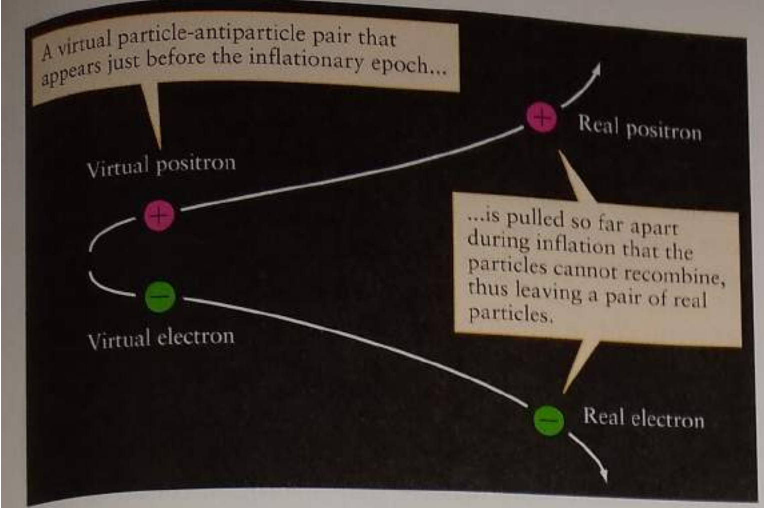


FIGURE 26-14

Inflation: From Virtual to Real Particles The universe expanded by such a tremendous factor during the inflationary epoch that the members of virtual particle-antiparticle pairs could no longer find each other. As a result, these virtual particles and antiparticles became real particles and antiparticles.

CONCEPTCHECK 26-6

Protons are about 2000 times more massive than electrons. If a virtual proton and antiproton spontaneously appear out of otherwise empty space, would this virtual pair last longer or shorter than a pair of virtual electrons before annihilating?

CONCEPTCHECK 26-7

Does the appearance of electrically charged virtual pairs violate the physical law that the total charge of an isolated system remains constant? (This law is also referred to as *conservation of charge*.)

Answers appear at the end of the chapter.

26-4 As the early universe expanded and cooled, most of the matter and antimatter annihilated each other

As soon as the flood of matter and antimatter appeared in the universe, collisions between particles and antiparticles began to produce numerous high-energy gamma rays. As these gamma rays collided, they promptly turned back into the particles and antiparticles from which they came. As a result, the rate of pair production soon equaled the rate of annihilation. For example, for every electron and positron that annihilated each other to create gamma rays (Figure 26-13b), two gamma rays collided elsewhere to produce an electron and a positron (Figure 26-13a). In other words, annihilation and pair production reactions proceeded with equal vigor, and as many particles and antiparticles were being created as were being destroyed.

As the universe continued to expand, all the gamma-ray photons became increasingly redshifted. As a result, the temperature of the radiation field fell. Due to their frequent interaction, radiation and particles of all kinds were in **thermal equilibrium:** All particle species, including photons, were at the same temperature. Hence, as the radiation temperature decreased, the temperature of particles of different types decreased as well.

From Quark Confinement to Particle-Antiparticle Annihilation

The first change in the population of particles and antiparticles occurred at $t = 10^{-6}$ second, when the temperature was 10^{13} K and particles were colliding with energies of roughly 1 GeV. Prior to this moment, particles collided so violently that individual protons and neutrons could not exist, being constantly fragmented into quarks. After this time, appropriately called the period of **quark confinement,** quarks were finally able to stick together and became confined within individual protons and neutrons.

LOOKING DEEPER 26.1

The cosmic background radiation we see today was spawned from a vast sea of particles and antiparticles in the early universe

As the universe continued to expand, temperatures eventually became so low that the gamma rays no longer had enough energy to create particular kinds of particles and antiparticles. We say that the temperature dropped below the particular particle's **threshold temperature.** Collisions between these types of particles and antiparticles continued to add photons to the cosmic-radiation background, but collisions between photons could no longer replenish the supply of particles and antiparticles.

At the same time that quark confinement became possible so that protons and neutrons appeared, the universe also became cooler than the 10^{13}-K threshold temperatures of both protons and neutrons. No new protons or neutrons were formed by pair production, but the annihilation of protons by antiprotons and of neutrons by antineutrons continued vigorously everywhere throughout space. This wholesale annihilation dramatically lowered the matter content (particles and antiparticles) of the universe, while simultaneously increasing the radiation (photon) content.

A little later, when the universe was about 1 second old, its temperature fell below 6×10^9 K, the threshold temperature for electrons and positrons. A similar annihilation of pairs of electrons and positrons further decreased the matter content of the universe while raising its radiation content. This radiation field, which fills all space, is the *primordial fireball* discussed in Section 25-5. This fireball, which dominated the universe for the next 380,000 years, therefore derived much of its energy from the annihilation of particles and antiparticles during the first second after the Big Bang.

Now we have a dilemma. If there had been perfect symmetry between particles and antiparticles, then for every proton there should have been an antiproton. For every electron, there should likewise have been a positron. Consequently, by the time the universe was 1 second old, every particle would have been annihilated by an antiparticle, leaving no matter at all in the universe.

Obviously, a total annihilation of all matter and antimatter never happened. The planets, stars, and galaxies we see in the sky are made of matter, not antimatter. If there were still substantial amounts of antimatter in the universe, it would eventually collide with ordinary matter. We would then see copious amounts of gamma rays being emitted from the entire sky. While we do observe gamma-ray photons from various locations in the universe, they are neither numerous enough nor of the right energy to indicate the presence of much antimatter. Thus, there must have been an excess of matter over antimatter immediately after the Big Bang so that the particles outnumbered the antiparticles.

Quite remarkably, we can estimate the extent of this initial asymmetry between matter and antimatter. In other words, while we essentially see a universe consisting of matter today, we can still infer how much antimatter there was before the antimatter portion of the universe annihilated with most of the matter portion. The key is light: Each annihilation of two particles produces exactly two photons (Figure 26-13b), and after being stretched to longer wavelengths, these are the photons we observe in the cosmic microwave background. As noted in Section 25-5, there are roughly 10^9 (one billion) photons today in the microwave background for each proton and neutron in the universe. Thus, for every 10^9 antiprotons, there must have been 10^9 plus one ordinary protons, leaving one surviving proton after annihilation. Similarly, for every 10^9 positrons, there must have been 10^9 plus one ordinary electrons.

While we can infer that the initial matter-antimatter asymmetry was about one additional particle made of regular matter per billion matter-antimatter pairs, we do not understand what process led to this initial asymmetry. There are several ideas for explaining the asymmetry but no hard evidence or agreement on a likely solution, and this initial asymmetry remains one of the great unsolved problems in physics and astronomy.

CONCEPTCHECK 26-8

Why does the following hypothesis seem unlikely: There is a perfect symmetry between matter and antimatter, but the antimatter is “somewhere else” and avoids annihilating with matter?

Answer appears at the end of the chapter.

26-5 A background of neutrinos and most of the helium in the universe are relics of the primordial fireball

The early universe must have been populated with vast numbers of neutrinos (ν) and their antiparticles, the antineutrinos ($\overline{\nu}$). These particles have a very small mass, so their threshold temperature is quite low. These particles take part in the nuclear reactions that transform neutrons into protons and vice versa. For example, a neutron can decay into a proton by emitting an electron and an antineutrino:

$$n \rightarrow p + e^- + \overline{\nu}$$

This radioactive decay happens quickly (its half-life is about 10.5 minutes), which is why we do not find free neutrons floating around in the universe today. In the first 2 seconds after the Big Bang, however, neutrons were also created by collisions between protons and electrons:

$$p + e^- \rightarrow n + \nu$$

This reaction kept the number of neutrons approximately equal to the number of protons. This balance was maintained only as long as collisions between protons and electrons were frequent. I
the number of electrons decreased precipitously as the temperat
of the universe fell below 6×10^9 K and electrons and positr
annihilated each other without being replenished (Section 26-4).
the time the universe was about 2 seconds old, no new neutr
were being formed, the natural tendency for neutrons to decay i
protons took over, and the number of neutrons began to decline

Spawning the First Nuclei

Before many of the neutrons could decay into protons, they began to combine with protons to form nuclei. Nuclei of helium,
the first element more massive than hydrogen, consist of ei
two protons and two neutrons (^{4}He) or two protons and a si
neutron (^{3}He). It is exceedingly improbable that two protons
one or two neutrons should all simultaneously collide with
another to form a helium nucleus. Instead, helium nuclei are b
in a series of steps. The first step is to have a single proton ar
single neutron combine to form deuterium (^{2}H), sometimes ca
“heavy hydrogen.” A photon (γ) is emitted in this process, so
write this reaction as

The first atomic nuclei formed within a quarter-hou after the Big Bang

$$p + n \rightarrow {}^2H + \gamma$$

Forming deuterium, however, does not immediately lea
the formation of helium. The problem is that deuterium n
are easily destroyed, because a proton and a neutron do not s
together very well. Indeed, in the early universe, high-en
gamma rays easily broke deuterium nuclei back down into i
pendent protons and neutrons. As a result, the synthesis of he
could not get beyond the first step. This block to the creatio
helium is called the **deuterium bottleneck**.

When the universe was about 3 minutes old, the backgro
radiation had cooled enough that its photons no longer
enough energy to break up the deuterium. By this time, mo
the neutrons had decayed into protons, and protons outn
bered neutrons by about 6 to 1. Because deuterium nuclei c
now survive, the remaining neutrons combined with protons
rapidly produced helium. (The Cosmic Connections: The Pro
Proton Chain figure for Chapter 16 depicts a similar sequen
reactions that take place in the core of the present-day Sun.)

The result was what we find in the universe today—abo
helium atom for every 10 hydrogen atoms. In addition to he
nuclei of lithium (Li, which has 3 protons) and beryllium
which has 4) were also produced in small numbers. The pro
of building up nuclei such as deuterium and helium from pro
and neutrons is called **nucleosynthesis** (Figure 26-15).

Because nuclei have positive electric charges, bringing
together to form more massive nuclei requires that they over
their mutual electric repulsion. They are unable to do so if
are moving too slowly, which will be the case if the temper
is too low. As a result, by about 15 minutes after the Big Ban
universe was no longer hot enough for nucleosynthesis to
place. Only the four lightest elements (hydrogen, helium, lith
and beryllium) were present in appreciable numbers. The he
elements would be formed only much later, once stars had fo
and nuclear reactions within those stars could manufacture
bon, nitrogen, oxygen, and all the other elements.

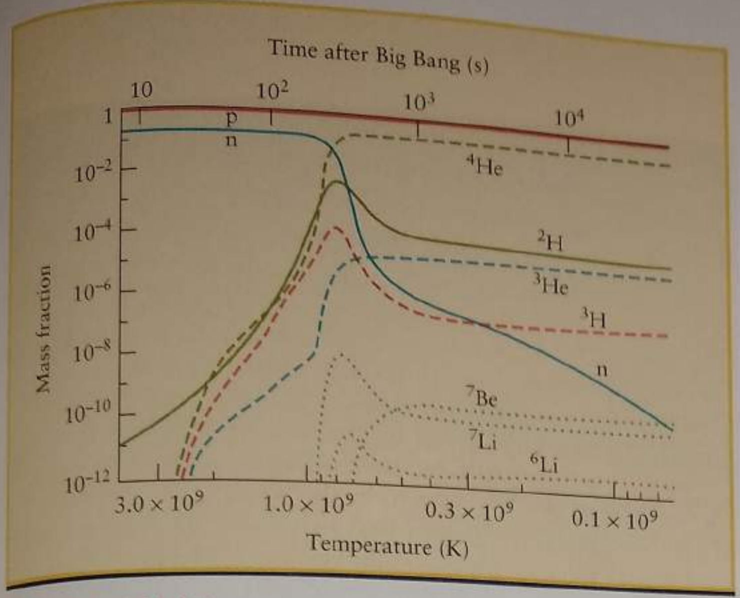


FIGURE 26-15

Nucleosynthesis in the Early Universe This graph shows how nuclei were produced between 10 seconds and 10 hours after the Big Bang. The vertical axis shows the fraction of the total mass that was in each type of particle or nucleus (p = proton, n = neutron, ^{2}H = deuterium, ^{3}He and ^{4}He = helium, ^{6}Li and ^{7}Li = lithium, ^{7}Be = beryllium). Very few nuclei were formed before the universe was 10 seconds old, due to the phenomenon of the deuterium bottleneck, which occurred at times earlier than those shown here. By about 10^3 seconds (roughly 15 minutes) after the Big Bang, the temperature had dropped below 4×10^8 K, no further nucleosynthesis was possible, and the relative amounts of different nuclei stabilized. The number of free neutrons declined rapidly as these particles decayed into protons, electrons, and antineutrinos. Agreement between these predicted mass fractions with what is observed today provides strong evidence for nuclear reactions in the early universe. (Adapted from R. V. Wagoner)

Nucleosynthesis was one of the great early successes of the Big Bang theory. At lower temperatures (to the right in Figure 26-15), the amounts of different nuclei leveled off and remains unchanged. That allows us to compare the amount of each predicted atomic element to the amount observed today, and the agreement is excellent. Furthermore, these nucleosynthesis calculations also predicted the density of ordinary matter in the universe, and this prediction has been verified by the CMB fluctuations as in Figure 25-22 and Table 25-2. Taken together, the success of nucleosynthesis provides very strong evidence for a hot Big Bang, and that during its first few minutes the entire universe was one big nuclear reactor.

CAUTION! Keep in mind that only *nuclei* formed in the first 15 minutes of the history of the universe. It would be another 380,000 years before temperatures became low enough for these nuclei to combine with electrons to form neutral atoms.

The Neutrino-Antineutrino Background

While nuclei were being formed in the early universe, what happened to all those primordial neutrinos and antineutrinos that had interacted so vigorously with the protons and neutrons before the universe was 2 seconds old? The answer is that by $t = 2$ seconds, matter was sufficiently spread out so that the universe became transparent to neutrinos and antineutrinos. From that time on, neutrinos and antineutrinos could travel across the universe unimpeded. Their interaction with matter is so weak that about a trillion neutrinos pass right through our bodies every second. Even Earth itself is virtually transparent to neutrinos from the Sun (Section 16-4).

The neutrinos and antineutrinos that were liberated at $t = 2$ seconds should now fill the universe much as the cosmic microwave background does. Indeed, these ancient neutrinos and antineutrinos may be about as populous today as the photons in the microwave background (of which there are 4.1×10^8 per cubic meter). The *neutrino-antineutrino background* should be slightly cooler than the photon background, which received extra energy from electron-positron annihilations. Physicists estimate that the current temperature of the neutrino-antineutrino background is about 2 K, as opposed to 2.725 K for the microwave background. Unfortunately, because neutrinos and antineutrinos are so difficult to detect, we do not yet have direct evidence of the neutrino-antineutrino background.

CONCEPTCHECK 26-9

How does the changing temperature of the universe confine the production of the elements helium, lithium, and beryllium to a period ranging from about 3 minutes to 15 minutes after the Big Bang?

Answer appears at the end of the chapter.

26-6 Galaxies and the first stars formed from density fluctuations in the early universe

The distribution of matter in the universe today is quite lumpy. Stars are grouped together in galaxies, galaxies into clusters, and clusters into superclusters that stretch across 50 Mpc (150 million ly) or more (see Section 23-6). Furthermore, galaxies seem to be concentrated along enormous sheets, which in turn surround voids measuring 30 to 120 Mpc (100 million to 400 million ly) across. Figures 23-23 and 23-24 show these features, which characterize the large-scale structure of the universe. How did this large-scale structure arise from the chaos of the primordial fireball? When did stars first appear in the universe? And when and how did galaxies first form?

Density Fluctuations and the Jeans Length

At first glance the origin of large-scale structure seems puzzling, because the early universe must have been exceedingly smooth. To see why, think back to the era of recombination that occurred 380,000 years after the Big Bang (see Section 25-5). Before recombination, high-energy photons were constantly and vigorously colliding with charged particles throughout all space. After recombination, the universe became transparent, and these photons stopped interacting with the matter in the universe. Astronomers say that matter "decoupled" from radiation during the era of recombination. Because the cosmic microwave background is extremely isotropic, we can conclude that the matter with which these photons once collided so frequently must also have been spread smoothly across space.

The distribution of matter during the early universe could not have been *perfectly* uniform, however. If it had been, it would still have to be absolutely uniform today; there would now be only a few atoms per cubic meter of space, with no stars and no galaxies. Consequently, there must have been slight lumpiness, or **density**

fluctuations, in the distribution of matter in the early universe. These fluctuations are thought to have originated in the very early universe, even before the inflationary epoch. Infinitesimally small quantum fluctuations in density, which are required by the Heisenberg uncertainty principle (see Section 26-3), were stretched during inflation to appreciable size. Through the action of gravity, these fluctuations initiated the clumping that eventually grew to become the galaxies and clusters of galaxies that we see today throughout the universe. As we saw in Section 25-5 and Section 25-8, the pattern of density fluctuations became imprinted on the cosmic background radiation during the era of recombination. Figure 25-13 shows a map of these fluctuations obtained from the WMAP microwave background spacecraft.

Our understanding of how gravity can amplify density fluctuations dates back to 1902, when the British physicist James Jeans solved a problem first proposed by Isaac Newton. Suppose that you have a gas with only very tiny fluctuations in density, as shown in Figure 26-16a. These regions of higher density will then gravitationally attract nearby material and thus gain mass. As the regions become more massive, however, the pressure of the gas inside these regions will also increase, which can make these regions expand and disperse. Jeans analyzed these opposing effects and asked the question: Under what conditions does gravity overwhelm gas pressure so that a permanent object can form?

Jeans proved that an object will grow due to a density fluctuation provided that the fluctuation extends over a distance that exceeds the so-called Jeans length (L_J):

Jeans length for density fluctuations

$$L_J = \sqrt{\frac{\pi k T}{m G \rho_m}}$$

L_J = Jeans length

k = Boltzmann constant = 1.38×10^{-23} J/K

T = temperature of the gas (in kelvins)

m = mass of a single particle in the gas (in kilograms)

G = universal constant of gravitation = $6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$

ρ_m = average density of matter in the gas

Density fluctuations that extend across a distance larger tha the Jeans length tend to grow, while fluctuations smaller than tend to disappear (Figure 26-16b).

We can apply the Jeans formula to the conditions that pr vailed during the era of recombination, when $T = 3000$ K ar $\rho_m = 10^{-18}$ kg/m^3. Taking m to be the mass of the hydrogen ato ($m = 1.67 \times 10^{-27}$ kg), we find that $L_J = 100$ light-years, th diameter of a typical globular cluster (Figure 26-17). Furthermor the mass contained in a cube whose sides are 1 Jeans length size (equal to the product of the density, ρ_m, and the volume the cube, L_J^3) is about 5×10^5 M$_\odot$, equal to the mass of a typic globular cluster. These calculations suggest that globular cluste were among the first objects to form after recombination.

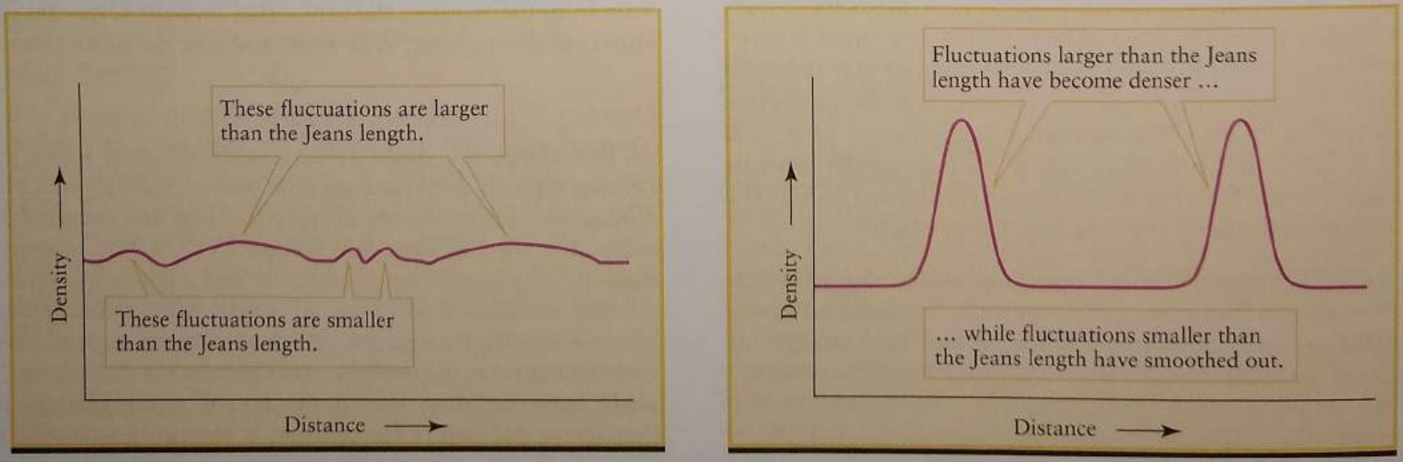
CONCEPTCHECK 26-10

Consider a density fluctuation around the era of recombinatio when the universe had a temperature of $T = 3000$ K. If the density fluctuation is about 10 light-years across, will the matter within that fluctuation begin clumping together? What [illegible] prevents clumping?

Answers appear at the end of the chapter.

Population III Stars: The "Zeroth" Generation

We saw in Section 19-4 that globular clusters contain the mo ancient stars we can find in the present-day universe. These a Population II stars with a low percentage of metals (elemen heavier than hydrogen and helium), and are of an earlier stell



(a) At an early time

(b) At a later time

FIGURE 26-16

The Growth of Density Fluctuations **(a)** This conceptual illustration shows small density fluctuations in the distribution of matter shortly after the era of recombination. **(b)** If the size of a fluctuation is greater than the Jeans length (L_J), it becomes gravitationally unstable and can grow in amplitude.

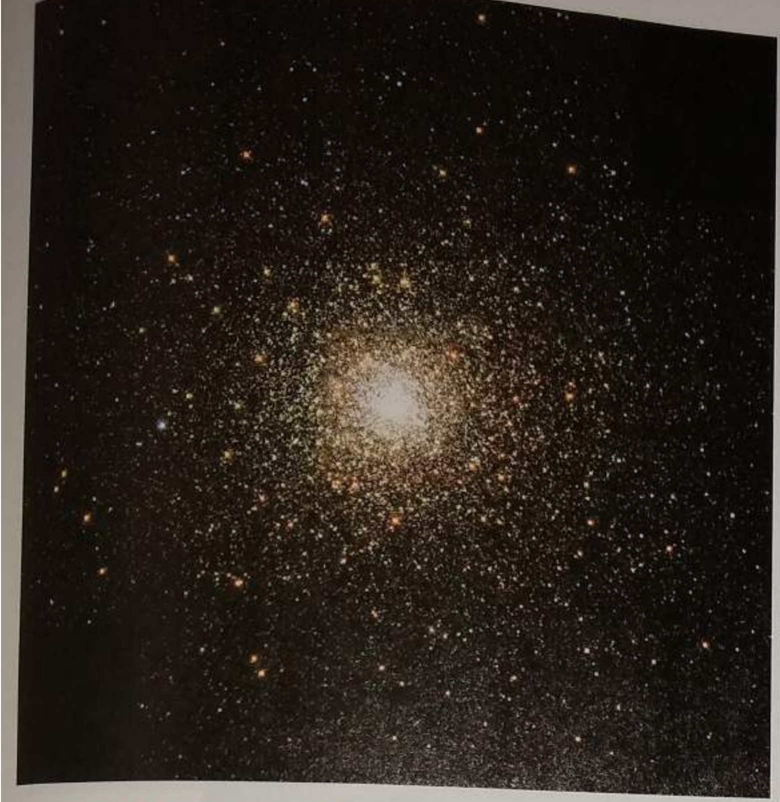


FIGURE 26-17 R I V U X G

A Globular Cluster A typical globular cluster contains 10^5 to 10^6 stars, each with an average mass of about 1 $M_\odot$, so the total mass of a typical cluster is 10^5–10^6 $M_\odot$. Cluster diameters range from about 6 to 120 pc (20 to 400 ly). Because these masses and diameters are comparable to the Jeans length (L_J) during the era of recombination, astronomers suspect that globular clusters were among the first objects to form in the universe. (Hubble Heritage Team/AURA/STScI/NASA)

generation than metal-rich Population I stars like the Sun (see Section 19-5). However, the Population II stars in globular clusters *cannot* be the very first stars to have formed after the Big Bang. Those first stars could have contained only hydrogen, helium, and tiny amounts of lithium and beryllium; as Figure 26-15 shows, these were the only elements whose nuclei formed in the early universe. Hence, these original stars would have contained an even smaller percentage of metals than the Population II stars found in globular clusters. Such "zeroth-generation" stars are called **Population III stars.**

ANIMATION 26-1

Like stars in the present-day universe, Population III stars would have formed from clouds of gas. These ancient gas clouds were composed almost exclusively of hydrogen and helium atoms, and such clouds have higher internal pressures than do metal-rich clouds of the same temperature. A star can form only when the mutual gravitation of the various parts of a cloud (which tends to make the cloud collapse) overcomes the internal pressure of the cloud (which tends to prevent collapse). Hence, Population III stars could form only if their mass (and hence their mutual gravitation) was rather large. Calculations suggest that these stars had masses from 30 to 1000 $M_\odot$, compared to the range of 0.4 to roughly 120 $M_\odot$ for modern stars. Even the smallest Population III star would rank among the largest stars observed today.

The "zeroth generation" of stars were much more massive and luminous than stars today

Although no Population III stars have yet been observed directly, we have at least indirect evidence that they existed. Infrared images from the Spitzer Space Telescope like the one that opens this chapter reveal a distant infrared background of starlight that is what we would expect to see from these zeroth-generation stars.

Another bit of evidence follows from the tremendous energy output of these stars: A 1000-$M_\odot$ Population III star would have been millions of times more luminous than the Sun and have a surface temperature in excess of 10^5 K, causing it to emit a flood of short-wavelength, high-energy photons. The photons from even a small number of such stars would have ionized most of the atoms in the universe, leaving electrons and nuclei of hydrogen and helium. This process is called **reionization,** a name that reminds us the universe had previously been ionized prior to recombination at $t = 380{,}000$ years. We saw in Section 25-8 that the photons of the cosmic microwave background are scattered by free electrons, and the effects of this scattering can be detected in maps of the background radiation. Data from the WMAP spacecraft suggest that reionization took place around 400 million years after the Big Bang, which in turn suggests that Population III stars formed around that time.

Since Population III stars were all very massive, their lifetimes were short and none could have survived to the present day. But during their short lifetimes, thermonuclear reactions within these stars produced elements heavier than beryllium for the first time in the history of the universe. What's more, calculations suggest that when these stars exploded—and due to their great mass, all of them did—they did not leave a white dwarf, neutron star, or black hole behind. Instead, all of their mass was ejected into space to be incorporated into the next generation of stars. The presence of heavy elements in the ejected material meant that when this material subsequently formed into clouds, the internal pressure of these clouds was lowered substantially and it became possible for low-mass stars to form. This laid the foundation for today's universe, in which dim, low-mass stars are common and luminous, massive stars are the exception (see Figure 17-5).

The era from recombination at $t = 380{,}000$ years to the first stars at $t = 400$ million years is called the **dark ages.** The only photons present at that time were those that make up today's cosmic background radiation. The dark ages ended when the universe was filled for the first time with the light from stars (Figure 26-18).

Forming Large-Scale Structure

Once clumps the size of globular clusters had formed in the universe, how did they form into galaxies, clusters of galaxies, and larger structures? One issue that complicates this matter is the presence of dark energy, which acts to accelerate the expansion of the universe (see Section 25-6). This accelerated expansion pulls clumps of material away from each other and makes it more difficult for them to coalesce into larger structures. Another complication is that about 85% of the mass in the universe is in the form of dark matter, whose nature is not known (see Section 23-8). Researchers

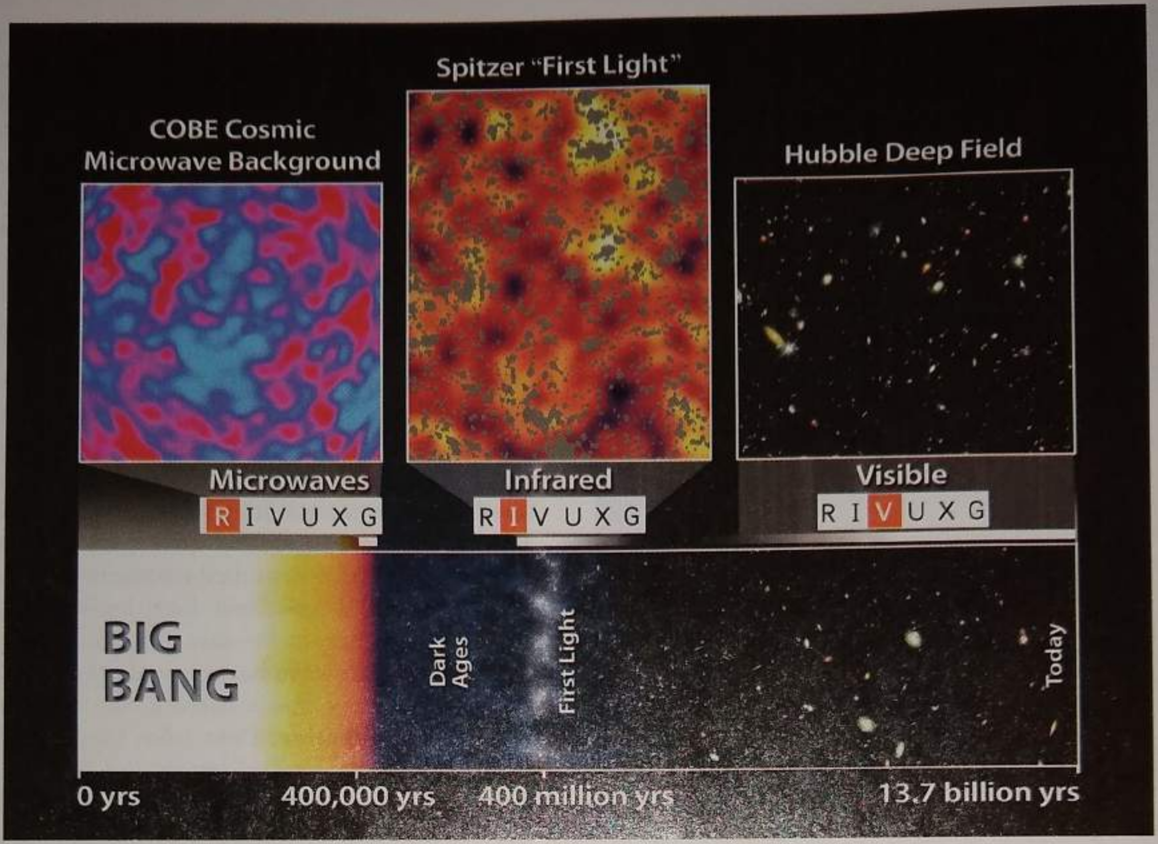


FIGURE 26-18

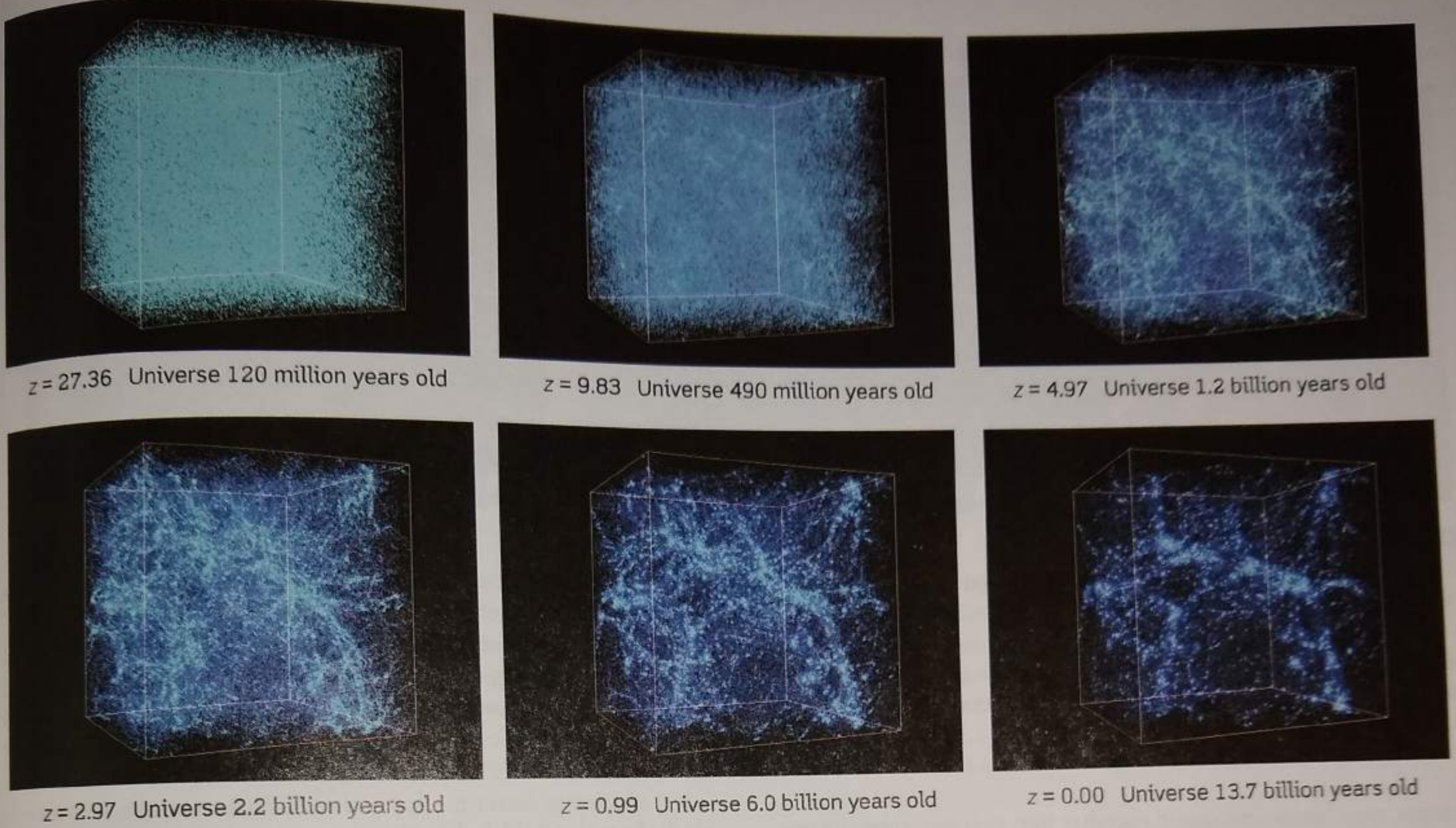
A Timeline of Light in the Universe The oldest light that we can see today is the cosmic background radiation, which comes from a time 380,000 years after the Big Bang when the universe first became transparent. This light has a redshift of about z = 1100 and appears in the microwave spectrum. Some 400 million years later at a redshift of about z = 11 the first stars appeared; their light is now redshifted to infrared wavelengths. Galaxies formed more recently and can be seen at visible wavelengths. (NASA; JPL-Caltech; and A. Kashlinsky, Goddard Space Flight Center)

have hypothesized different types of dark matter in the hope of explaining the large-scale structure that we see. Neutrinos are an example of **hot dark matter,** so named because it consists of light-weight particles traveling at high speeds. **Cold dark matter,** on the other hand, consists of massive particles traveling at slow speeds. Examples include WIMPs (which we discussed in Section 22-4) as well as other exotic, speculative particles.

Scientists use supercomputer simulations to see how different types of dark matter would influence the development of large-scale structure. Figure 26-19 shows the results of such a simulation for a flat universe with dark energy and *cold* dark matter. The simulation follows the motions of 2 million particles of cold dark matter in a box that expands as the universe expands. The box at the lower right of the figure, representing the present time (redshift $z = 0$) is 43 Mpc (160 million ly) a side. At earlier times, the box represents a volume whose side is smaller by a factor $1/(1 + z)$. For example, each side of the box for $z = 0.99$ is actually 1/1.99 as long as the box for $z = 0$.

The simulation begins 120 million years after the Big Bang with an almost perfectly uniform distribution of particles, mimicking the tiny density fluctuations that must have been present just after inflation. A supercomputer then calculates how these particl move, based on Newton's laws in an expanding universe. As tim goes on, the fluctuations grow into small, bright clumps whos sizes and masses are similar to those of galaxies. A large filamen also forms, spanning the entire box from left to right. The simulation shows that no additional structures formed after the univers was about 6 billion years old, corresponding to redshift $z = 1$. Th explanation is that after this time, the accelerating expansion o the universe becomes more important than gravitational attractio The final frame of the simulation strongly resembles actual maps o galaxies in our present-day universe (see Figure 23-24).

Simulations similar to those in Figure 26-19 have also bee carried out using *hot* dark matter in the form of neutrinos. massless neutrino would always travel at the speed of light, just a a photon does. However, experiments show that neutrinos do hav a small mass. (This nonzero mass is what allows one type of neutrino to transform into another. We saw in Section 16-4 that suc transformations provided the explanation to the long-standin solar neutrino problem.) Hence, neutrinos travel slower than ligh and slow down as the universe expands and cools. Slow-movin neutrinos would accumulate over time within density fluctuations



ANIMATION 26-2 ANIMATION 26-3

FIGURE 26-19
A Cold Dark Matter Simulation with Dark Energy These six views show the evolution of dark matter particles in a large, box-shaped volume of space. The box actually expands with time to follow the expansion of the universe and holds the same number of particles. In this figure, the boxes have been rescaled so they all appear at the same size. Small fluctuations in density are put into the simulation at the beginning (at upper left); these evolve over time to form structures that resemble those actually observed in our present-day universe ($z = 0.00$, shown at the lower right). (Applications by Andrey Kravtsov, University of Chicago, and Anatoly Klypin, New Mexico State University; visualizations by Andrey Kravtsov)

and the gravitational pull of these neutrinos on surrounding matter could eventually lead to the formation of clusters of galaxies.

A primary difference between simulations based on cold and hot dark matter is the way in which galaxies form. In calculations based on cold dark matter, the formation of galaxies takes place from the “bottom up.” In these simulations, the densest gas undergoes collapse early in the history of the universe and stars begin to form. The regions of star formation stream along the filaments (Figure 26-20). When they meet at the intersections between

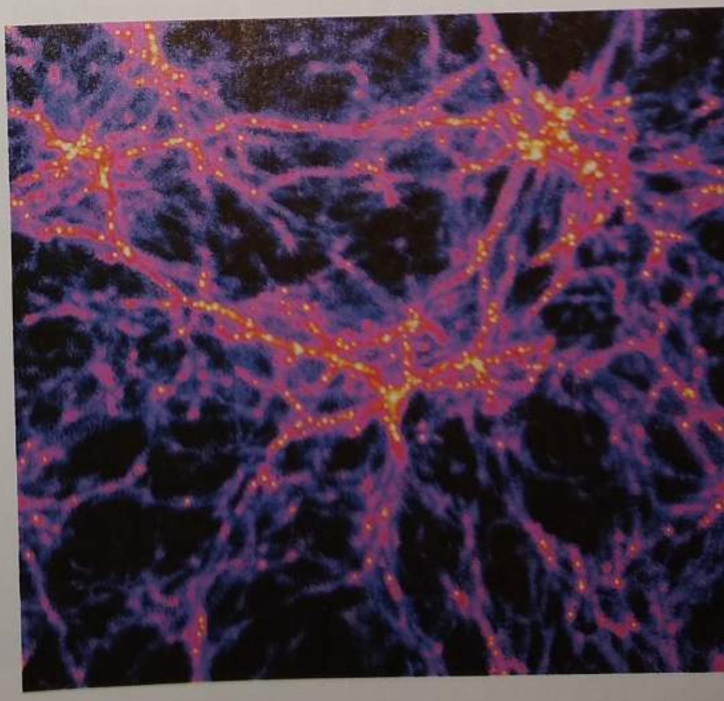
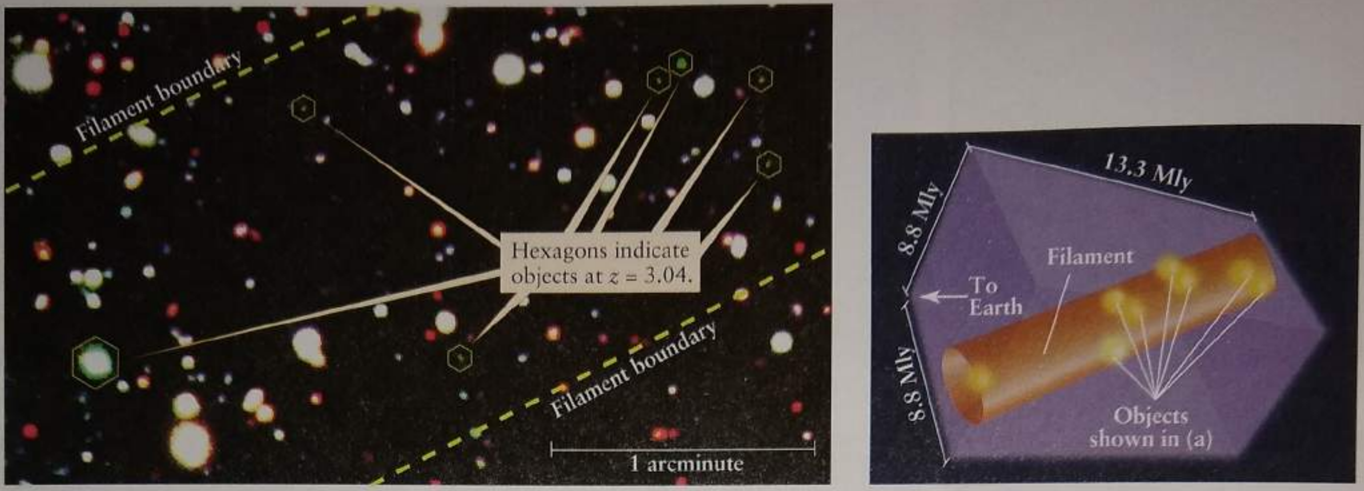


FIGURE 26-20
“Bottom-Up” Galaxy Formation: Simulation This image is taken from a cold dark matter simulation like that shown in Figure 26-15. A portion of the universe is shown at a time 2.2 billion years after the Big Bang, corresponding to redshift $z = 3.04$. The colors indicate the density of gas: Yellow is highest, red is medium, and blue is the lowest density. Over time, the gas tends to pile up at points where filaments intersect, forming galaxies and clusters of galaxies. (T. Theuns, MPA Garching/ESO)



(a) High-redshift objects that lie within a filament

(b) Illustration of the filament

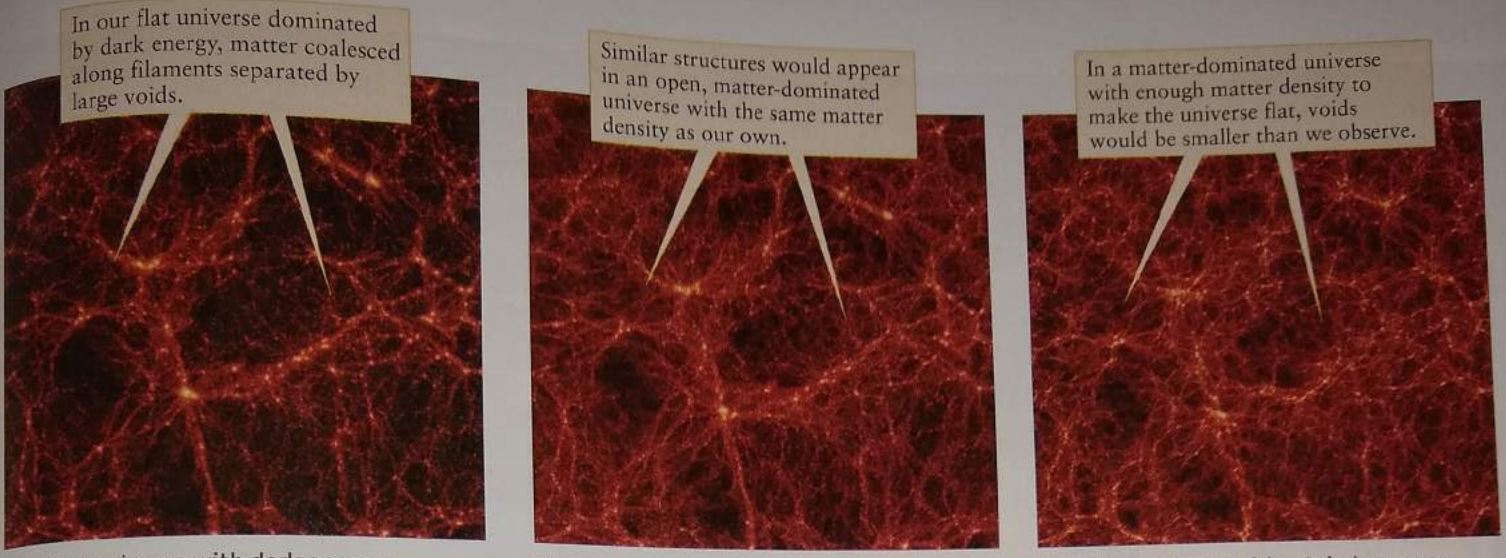
FIGURE 26-21 R I V U X G

"Bottom-Up" Galaxy Formation: Observation **(a)** The hexagons in this image from the Very Large Telescope show the positions of a number of sub-galaxy-sized objects at a redshift $z = 3.04$, the same as in the simulation shown in Figure 26-16. Excited hydrogen atoms in these objects emit ultraviolet photons, which are redshifted to visible wavelengths. This redshifted emission gives these objects a characteristic green color. (The object at l left actually lies in front of a much brighter quasar.) **(b)** The objects in (a) a lie within an immense filament. The purple box shows the volume of spac studied in this observing program. The dimensions are given in millions of light-years (Mly). (European Southern Observatory)

filaments, they merge and group together into galaxies, then clusters of galaxies, then superclusters. But in calculations based on hot dark matter, galaxies form from the "top down." Huge supercluster-sized sheets of matter form first and then fragment into galaxies. Observations of remote galaxies show that galaxies actually formed from the "bottom up" scenario. One piece of evidence for this is the image in Figure 26-21a, which shows a handful of "galaxy building blocks" at $z = 3.04$ (when the universe was 2.2 billion years These "building blocks," which have not yet coalesced into ga ies, lie within a long filament (see Figure 26-21b) that resem those shown in the simulation of Figure 26-20. Figure 26-22 sh a collection of "building blocks" at a later stage in the proces merging into a galaxy. These observations strongly suggest that dominant form of dark matter is cold, not hot.

FIGURE 26-22 R I V U X G

A Galaxy Under Construction This Hubble Space Telescope image shows dozens of small galaxies in the process of merging into a single large galaxy. We see this galaxy at a redshift $z = 2.2$, corresponding to a time 3.1 billion years after the Big Bang. (NASA; ESA; G. Miley and R. Overzier, Leiden Observatory; and the ACS Science Team)



(a) A flat universe with dark energy: $\Omega_m = 0.3, \Omega_\Lambda = 0.7$

(b) A open universe without dark energy: $\Omega_m = 0.3, \Omega_\Lambda = 0$

(c) A flat universe without dark energy: $\Omega_m = 1.0, \Omega_\Lambda = 0$

FIGURE 26-23

Using Simulations to Constrain the Matter Density of the Universe Cold dark matter simulations like those in Figures 26-15 and 26-16 help astronomers determine the value of the matter density parameter Ω_m. These three simulations show a portion of the universe at $z = 0$. **(a)** A simulation with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, close to the values for our universe, gives a good match to the observed distribution of filaments and voids. **(b)** Nearly as good a match is obtained if we keep $\Omega_m = 0.3$, but eliminate dark energy so that $\Omega_\Lambda = 0$. **(c)** If we use a larger value of Ω_m, the distribution of matter in the simulation is a poor match to our universe. (Simulation by the Virgo Supercomputing Consortium using computers based at the Computer Centre of the Max Planck Society in Garching and at the Edinburgh Paralle Computer Centre)

What Large-Scale Structure Reveals

How might the universe have evolved if it had contained different amounts of cold dark matter and dark energy? Figure 26-23 shows some simulations designed to explore these possibilities. If the density of matter in the universe is kept constant for various simulations, the simulations predict approximately the same structure for different values of the dark energy density parameter Ω_Λ defined in Section 25-6 (see Figure 26-23a and Figure 26-23b). But if too large a matter density is used in the simulation, the voids between galaxies are smaller than what we actually observe in our universe (Figure 26-23c). Hence, observations of galaxy clustering coupled with supercomputer simulations of galaxy formation help determine the matter density of our universe. (We made use of this idea in Section 25-7. The brown band in Figure 25-18 shows the constraints on cosmological parameters from these observations and simulations of galaxies.)

The best match to the observed distribution of galaxy clusters and to the cosmic background radiation data (see Figure 25-22) is a model like that shown in Figure 26-19, with dark energy and cold dark matter in the proportions listed in Table 25-2.

Cosmic Connections: The History of the Universe summarizes the past history of our universe down to the present day. As we discussed in Section 25-7, the *future* of our universe is less certain and depends on the detailed character of dark energy. More detailed data about galaxy clusters and the cosmic background radiation will be needed to pin down the future evolution of universe.

CONCEPTCHECK 26-11

How does structure formation in the early universe provide clues to the nature of dark matter?

Answer appears at the end of the chapter.

26-7 String theory attempts to unify the fundamental forces and predicts that the universe may have 11 dimensions

While we have a growing understanding of the early universe,
remains a veil obscuring the first 10^{-43} seconds after the Big
These very *first* moments in the history of the universe, whose
tion was the Planck time, set the stage for what would come
To understand this brief interval, we need to construct a qua
mechanical theory that unifies gravity with the other fundar
forces of nature and that reconciles quantum mechanics
gravity—a theory of quantum gravity. While unification rema
unfinished task, remarkable progress has been made in recent
One major development is that physicists have abandoned th
that there are only three dimensions of space.

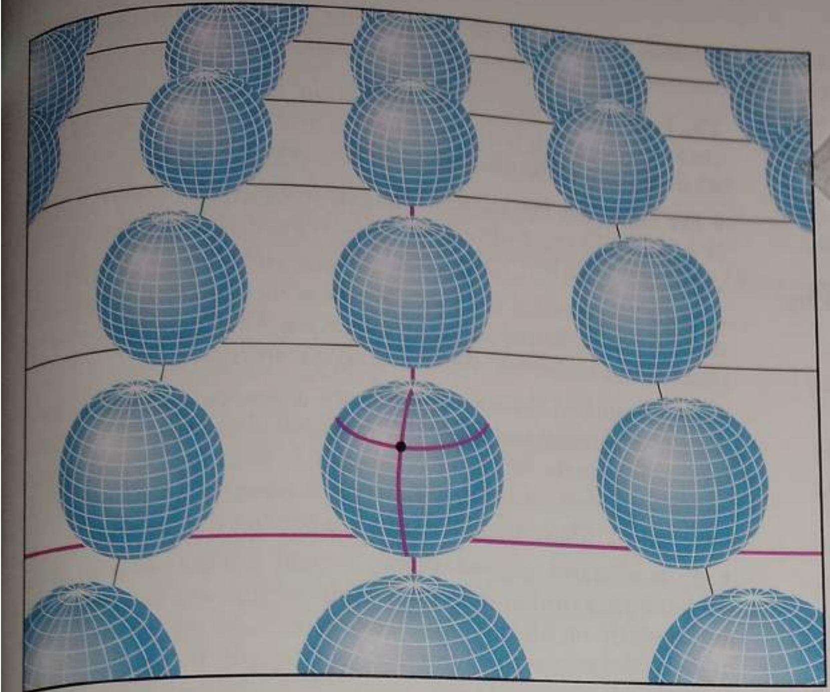


FIGURE 26-24

Hidden Dimensions of Space Hidden dimensions of space might exist provided they are curled up so tightly that we cannot observe them. This drawing shows how an ordinary two-dimensional plane might contain two additional dimensions. At every point on the plane, there is a very tiny sphere so small that it cannot be seen. To pinpoint a particular location, you need to give not only a position on the plane but also a position on the sphere. Thus, if at every point, space really has additional curled up dimensions represented by these spheres, then space has more than the three regular dimensions of space we are familiar with. Like a hamster running endlessly on its wheel, moving in a curled up dimension is not the same as traveling through regular space. (Adapted from D. Freedman and P. Van Nieuwenhuizen)

Beyond Four Dimensions

In his special and general theories of relativity, Einstein combined time with the three known dimensions of ordinary space, resulting in a four-dimensional combination called *spacetime* (see Section 21-1). In 1919, the Polish physicist Theodor Kaluza proposed the existence of a *fifth* dimension. Kaluza hoped to describe both gravity and electromagnetism in terms of the curvature of five-dimensional spacetime, just as Einstein had explained gravity by itself in terms of the curvature of four-dimensional spacetime (see Section 21-2).

In Kaluza's theory, a particle always follows the straightest possible path in the four space dimensions he proposed. But in the three dimensions of ordinary space, the path appears curved. Hence, it appears to us that the particle has been deflected—by force—and this is Kaluza's mechanism to describe gravitational and electromagnetic forces. Kaluza's hypothetical fifth dimension exists at every point in ordinary space but is curled up so tightly, like a very tiny sphere, that it is not directly observable (Figure 26-24).

In 1926, the Swedish physicist Oskar Klein attempted to make Kaluza's five-dimensional theory compatible with quantum mechanics. While he was not successful, Klein discovered that particles of different masses could be identified with different vibrations occurring in the tiny sphere of Kaluza's fifth dimension.

String Theory and Speculative Models of the Universe

When Kaluza and Klein developed their theories, gravity and electromagnetism were the only known forces of nature. Today we know of four fundamental forces, which suggests that modern unification theories might require even more than five dimensions. Edward Witten at Princeton University has argued that a geometric theory for describing all four forces would work best with 11 dimensions, 10 of space and 1 of time. These models that attempt to unify all the forces of nature, including a quantum mechanical description of gravity, are called string theory. (There are also related names, such as superstring theory and M-theory.)

Subatomic particles may actually be multidimensional membranes

We see only the regular three dimensions of space, and one dimension of time. As with Kaluza's theory, particles traveling straight in 11-dimensional space would appear to take curved paths in ordinary three-dimensional space. From our perspective, these curved paths would be the result of the four known forces acting on the particles.

Theoretical physicists have shown that if there are indeed 11 dimensions, there must also exist very massive particles that have not yet been discovered. The more massive the particle, the more energy is required in particle accelerators to create and observe it, and particle accelerators might not ever be able to reach these very high energies. Some of these speculative particles may be the dark matter that pervades the universe. Even more bizarre, the new theories no longer regard fundamental particles, such as electrons and quarks, as tiny points of mass. Instead, these particles may actually be multidimensional strings or membranes, wrapped so tightly around the extra dimensions of space that they appear to us as points. Just as a guitar can vibrate in different ways to make different sounds, vibrations of these fundamental strings correspond to different particles and the forces between them.

One criticism of string theory is that its predictions are too far beyond the energies that can foreseeably be tested. However, when the extremely large energies of the Big Bang are considered, proponents of string theory hope that the early universe itself will have acted as a powerful cosmic particle accelerator that left behind telling evidence. In this manner, astronomy might be used to gather evidence for strings whose vibrations lead to all the known forces in nature.

CONCEPTCHECK 26-12

If, as suggested by string theory, there really are 11 dimensions, why don't we notice them? How many dimensions appear to be hidden?

Answer appears at the end of the chapter.

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

T. S. Eliot, *Four Quartets*

KEY WORDS

annihilation, p. 766
antimatter, p. 765
antiparticle, p. 765
antiproton, p. 765
cold dark matter, p. 772
cosmic light horizon, p. 756
dark ages, p. 771
density fluctuation, p. 769
deuterium bottleneck, p. 768
electroweak force, p. 761
elementary particle physics, p. 764
false vacuum, p. 763
flatness problem, p. 757
gluon, p. 760
grand unified theory (GUT), p. 763
graviton, p. 763
Heisenberg uncertainty principle, p. 765
hot dark matter, p. 772
inflation, p. 757
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intermediate vector boson, p. 760
isotropy problem (horizon problem), p. 756
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M-theory, p. 777
nuclear force, p. 759
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supergrand unified theory, p. 763
theory of everything (TOE), p. 763
thermal equilibrium, p. 767
threshold temperature, p. 767
virtual pairs, p. 766
weak force, p. 759

KEY IDEAS

Cosmic Inflation: 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.

The Four Forces and Their Unification: Four basic forces—gravity, electromagnetism, the strong force, and the weak force—explain all the interactions observed in the universe.

- The Standard Model accurately describes all the known particles in nature and their observed interactions (except for gravity).
- The weak force and electromagnetic force become unified into a single force called the electroweak force at higher energies than those typically found in today's universe. This unification has been observed in high-energy particle accelerators.
- Grand unified theories (GUTs) are attempts to explain three o the forces (strong force, weak force, and electromagnetic force) in terms of a single force. This has not been observed, and particl accelerators fall far short of having the energy to directly probe th high energy where this unification is predicted to occur.
- A supergrand unified theory would explain all four force (including gravity) at extremely high energies as a single force act ing similarly on all the particles in nature. String theory attempt to make this unification, and it would describe the quantum natur of gravity. Supergrand unification is hypothesized to occur befor the Planck time ($t = 10^{-43}$ seconds after the Big Bang).

Spontaneous Symmetry Breaking: As the universe expands an cools, the unified forces break into separate forces. Starting aroun the Planck time, gravity became a distinct force through a spont neous symmetry breaking. During a second spontaneous symmet breaking, the strong nuclear force became a distinct force. A fin spontaneous symmetry breaking separated the electromagnet force from the weak nuclear force; from that moment on, the un verse behaved as it does today.

Particles and Antiparticles: Heisenberg's uncertainty princip states that the amount of uncertainty in the mass of a subatom particle increases as it is observed for shorter and shorter ti periods.

- Because of the uncertainty principle, particle-antiparticle pa can spontaneously form and disappear within a fraction of a s ond. These pairs, whose presence can be detected only indirect are called virtual pairs.
- The collision of two high-energy photons can produce a r particle-antiparticle pair. In this process, called pair producti the photons disappear, and their energy is transformed into masses of the particle-antiparticle pair. In the process of annihi tion, a colliding particle-antiparticle pair disappears and two hi energy photons appear.

The Origin of Matter: Just after the inflationary epoch, universe was filled with particles and antiparticles formed fr numerous high-energy photons. The particles also annihilated produce a state of thermal equilibrium between the particles a the photons.

- As the universe expanded, its temperature decreased. W the temperature fell below the threshold temperature required produce each kind of particle, annihilation of that kind of part began to dominate over production.