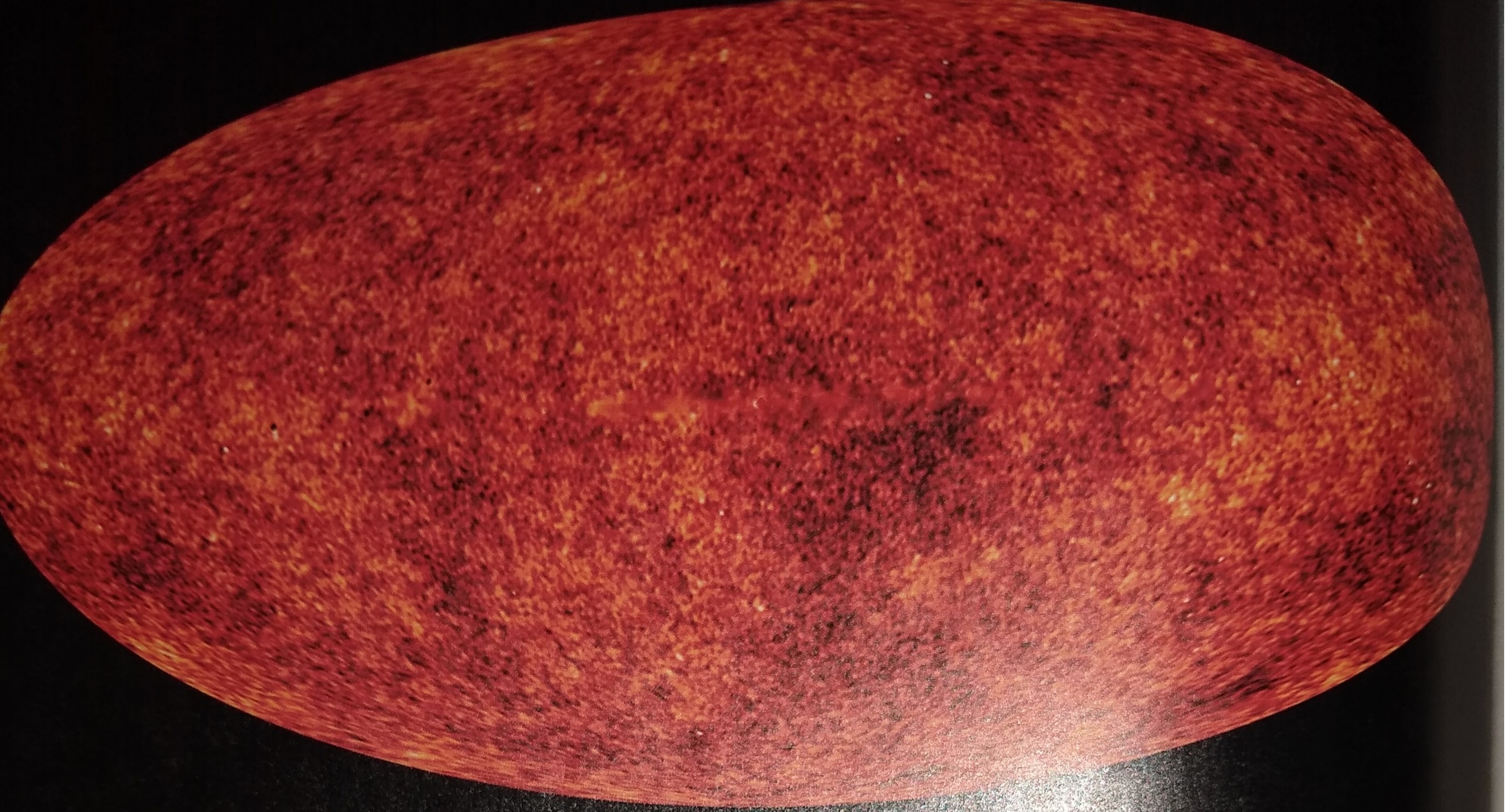


22

THE BIRTH OF THE UNIVERSE

LEARNING GOALS

22.1 THE BIG BANG THEORY

- What were conditions like in the early universe?
- How did the early universe change with time?

22.2 EVIDENCE FOR THE BIG BANG

- How do observations of the cosmic microwave background support the Big Bang theory?
- How do the abundances of elements support the Big Bang theory?

22.3 THE BIG BANG AND INFLATION

- What key features of the universe are explained by inflation?
- Did inflation really occur?

22.4 OBSERVING THE BIG BANG FOR YOURSELF

- Why is the darkness of the night sky evidence for the Big Bang?

Somewhere, something incredible is waiting to be known.

—Carl Sagan

Throughout this book, we have studied how the matter produced in the early universe gradually assembled to make galaxies, stars, and planets. However, we have not yet answered one big question: Where did the matter itself come from?

To answer this question, we must go beyond the most distant galaxies and even beyond what we can see near the horizon of the universe. We must go back not just to the origins of matter and energy but all the way back to the beginning of time itself. As we will see, while many questions about the birth of the universe remain unanswered, we now seem to have some understanding of events that must have unfolded as far back as the first fraction of a second after the Big Bang.

MA **Hubble's Law Tutorial, Lessons 1–3**

22.1 THE BIG BANG THEORY

Is it really possible to study the origin of the entire universe? Not long ago, this topic was considered unfit for scientific study. Scientific attitudes began to change with Hubble's discovery that the universe is expanding, which led to the insight that all things very likely sprang into being at a single moment in time, in an event that we have come to call the *Big Bang*. Today, powerful telescopes allow us to view how galaxies have changed over the past 14 billion years, and at great distances we see young galaxies still in the process of forming [**Section 21.1**]. These observations confirm that the universe is gradually aging, as expected for a universe with an age of 14 billion years.

Unfortunately, we cannot see back to the very beginning of time. Light from the most distant galaxies observed to date shows us what the universe looked like when it was a few hundred million years old. Observing light from earlier times is more difficult because it means looking back to a time before stars existed. Ultimately, however, we face an even more fundamental problem. The universe is filled with a faint glow of radiation that appears to be the remnant heat of the Big Bang. This faint glow is light that has traveled freely through space since the universe was about 380,000 years old, which is when the universe first became transparent to light. Before that time, light could not pass freely through the universe, so there is no possibility of seeing light from earlier times. Just as we must rely on theoretical modeling to determine what the Sun is like on the inside, we must also use modeling to investigate what the universe was like during its earliest moments.

The scientific theory that predicts what the universe was like early in time is called the **Big Bang theory**. It is based on applying known and tested laws of physics to the idea that everything we see today began as an incredibly hot and dense collection of matter and radiation. The Big Bang theory successfully describes how expansion and cooling of this unimaginably intense mixture of particles and photons could have led to the present universe of stars and galaxies, and it explains several aspects of today's universe with impressive accuracy. Our main goal in this chapter is to understand the evidence supporting the Big Bang theory, but first we must explore what the theory tells us about the early universe.

What were conditions like in the early universe?

Observations demonstrate that the universe is cooling with time as it expands, implying that it must have been hotter and denser in the past. Calculating exactly how hot and dense the universe must have been when it was more compressed is much like calculating how the temperature and density of gas in a balloon change when you squeeze it, except that the conditions become much more extreme. **FIGURE 22.1** shows how the temperature of the universe has changed with time, according to such calculations.

For most of the universe's history, even back to times just minutes after the Big Bang, conditions were no more extreme than those found in many places in the universe today, such as in the interiors of stars, and therefore can be understood with the same laws of physics that we've applied throughout most of this book. However, at very early times, temperatures were so high that different processes came into play. To understand what the Big Bang theory tells us about events

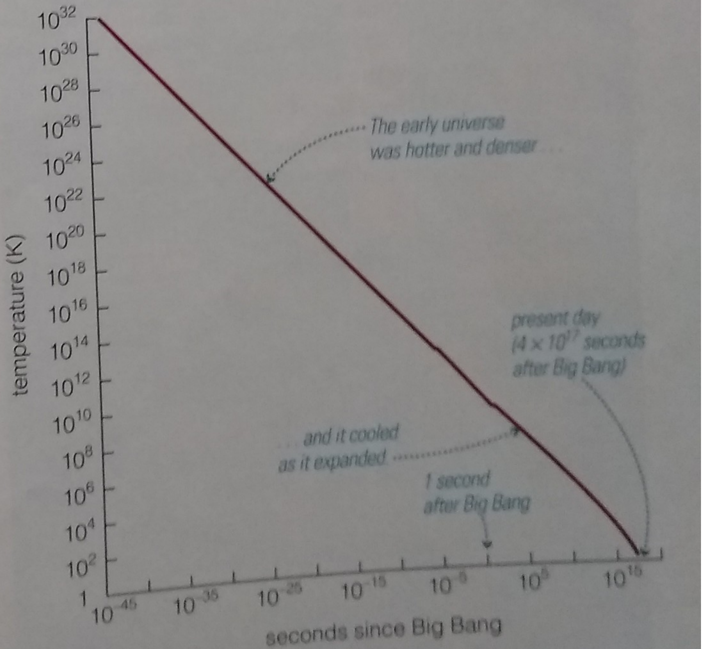


FIGURE 22.1 The universe cools as it expands. This graph shows results of calculations that tell us how the temperature has changed with time. Notice that both axis scales use powers of 10; therefore, even though most of the graph shows temperatures during the first second of the Big Bang, the far right part of the graph actually extends to the present (14 billion years ≈ 4×10^{17} s). The kinks correspond to periods of matter-antimatter annihilation.

at those times, we must become more familiar with two aspects of high-energy physics: the creation and annihilation of particles, and the relationships between the fundamental forces that govern matter and energy in the universe.

Particle Creation and Annihilation The universe was so hot during the first few seconds that photons could transform themselves into matter, and vice versa, in accordance with Einstein's formula, $E = mc^2$ [**Section 4.3**]. Reactions that create and destroy matter are now relatively rare in the universe at large, but physicists can reproduce many such reactions in particle accelerators such as the Large Hadron Collider [**Section S4.1**].

One such reaction is the creation or destruction of an *electron–antielectron pair* (FIGURE 22.2). When two photons collide with a total energy greater than twice the mass-energy of an electron (the electron's mass times c^2), they can create two brand-new particles: a negatively charged electron and its positively charged twin, the *antielectron* (also known as a *positron*). The electron is a particle of **matter**, and the antielectron is a particle of **antimatter**. The reaction that creates an electron–antielectron pair also runs in reverse. When an electron and an antielectron meet, they *annihilate* each other totally, transforming all their mass-energy back into photon energy. In order to conserve both energy and momentum, an annihilation reaction must produce two photons instead of just one.

Similar reactions can produce or destroy any particle–antiparticle pair, such as a proton and an antiproton or a neutron and an antineutron. The early universe therefore was filled with an extremely hot and dense blend of photons, matter, and antimatter, converting furiously back and forth. Despite all these vigorous reactions, describing conditions in the early universe is straightforward, at least in principle. We simply need to use the laws of physics to calculate the proportions of the various forms of radiation and matter at each moment in the universe's early history. The only difficulty is our incomplete understanding of the laws of physics.

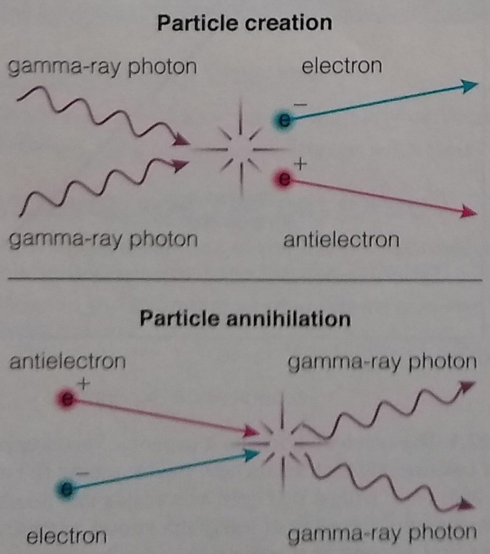


FIGURE 22.2 Electron–antielectron creation and annihilation. Reactions like these constantly converted photons to particles, and vice versa, in the early universe.

To date, physicists have investigated the behavior of matter and energy at temperatures as high as those that existed in the universe just *one ten-billionth* (10^{-10}) of a second after the Big Bang, giving us confidence that we actually understand what was happening at that early moment in the history of the universe. Our understanding of physics under the more extreme conditions that prevailed even earlier is less certain, but we do have some ideas about what the universe was like when it was a mere 10^{-38} second old, and perhaps a glimmer of what it was like at the age of just 10^{-43} second. These tiny fractions of a second are so small that, for all practical purposes, we are studying the very moment of creation—the Big Bang itself.

Fundamental Forces To understand the changes that occurred in the early universe, it helps to think in terms of *forces*. Everything that happens in the universe today is governed by four distinct forces: *gravity, electromagnetism*, the *strong force*, and the *weak force* [**Section S4.2**]. We have already encountered examples of each of these forces in action.

Gravity is the most familiar of the four forces, providing the "glue" that holds planets, stars, and galaxies together. The electromagnetic force, which depends on the electrical charge of a particle instead of its mass, is far stronger than gravity. It is therefore the dominant force between particles in atoms and molecules, responsible for all chemical and biological reactions. However, the existence of both positive and negative electrical charges causes the electromagnetic force to lose out to gravity on large scales, even though both forces decline with distance by an inverse square law. Most large astronomical objects (such as planets and stars) are electrically neutral overall, making the electromagnetic force unimportant on that scale. Gravity therefore becomes the dominant force for such objects, because more mass always means more gravity.

The strong and weak forces operate only over extremely short distances, making them important within atomic nuclei but not on larger scales. The strong force binds atomic nuclei together [**Section 14.2**]. The weak force plays a crucial role in nuclear reactions such as fission and fusion, and it is the only force besides gravity that affects weakly interacting particles such as neutrinos.

Although the four forces behave quite differently from one another, current models of fundamental physics predict that they are just different aspects of a smaller number of more fundamental forces, probably only one or two (FIGURE 22.3). These models predict that the four forces would have been merged together at the high temperatures that prevailed in the early universe.

As an analogy, think about ice, liquid water, and water vapor. These three substances are quite different from one another in appearance and behavior, yet they are just different phases of the single substance H_2O. In a similar way, experiments have shown that the electromagnetic and weak forces lose their separate identities under conditions of very high temperature or energy and merge together into a single **electroweak force**. At even higher temperatures and energies, the electroweak force may merge with the strong force and ultimately with gravity. Theories that predict the merger of

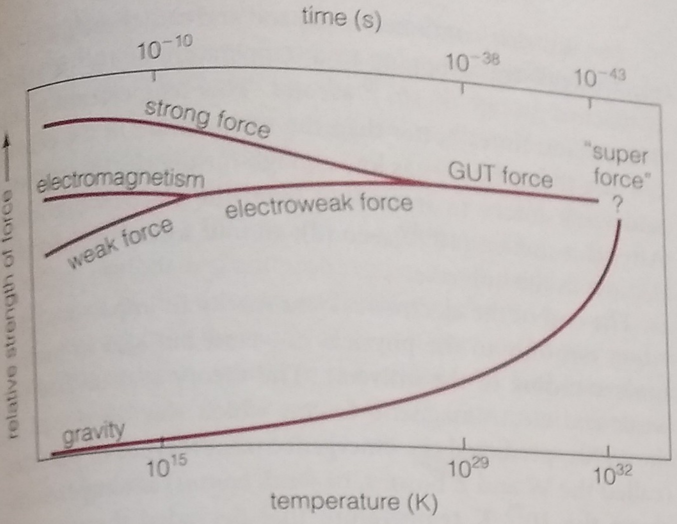


FIGURE 22.3 The four forces are distinct at low temperatures but may merge at very high temperatures, such as those that prevailed during the first fraction of a second after the Big Bang.

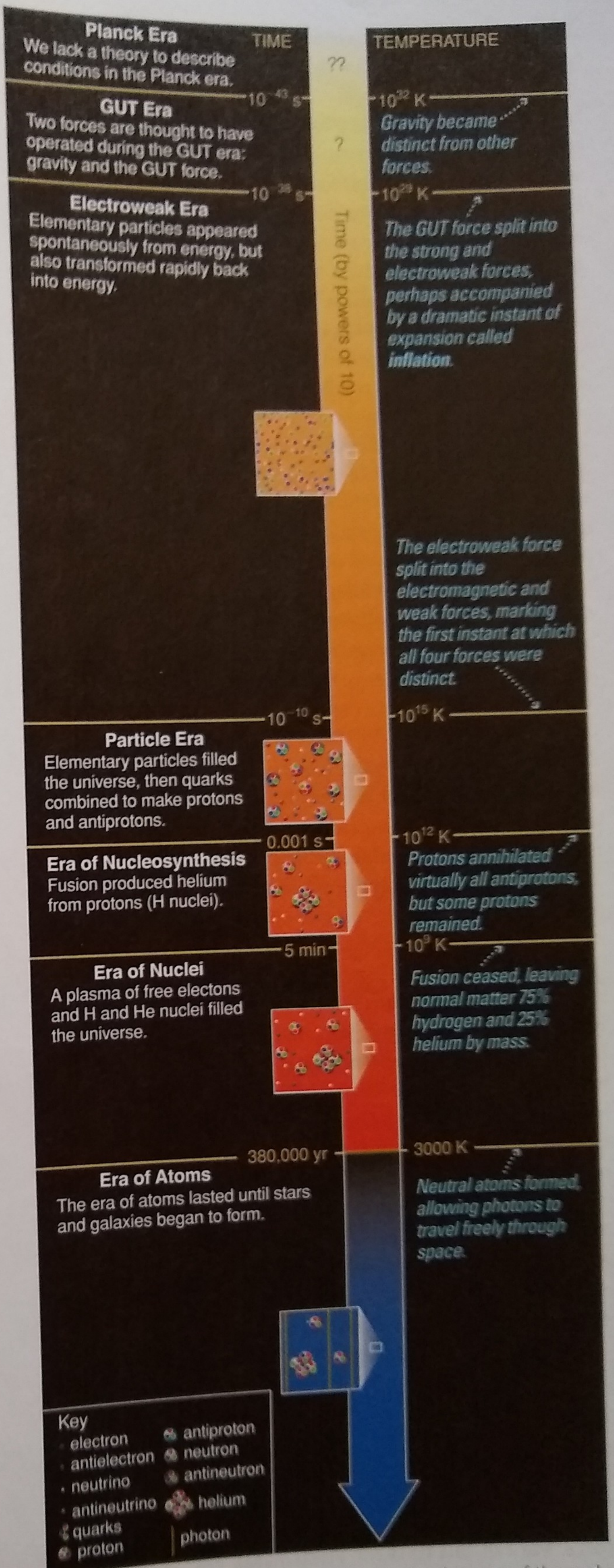
the electroweak and strong forces are called **grand unified theories**, or **GUTs** for short. The merger of the strong, weak, and electromagnetic forces is therefore often called the *GUT force*. Many physicists suspect that at even higher energies, the GUT force and gravity merge into a single "super force" that governs the behavior of everything. (You may also hear the names *supersymmetry*, *superstrings*, and *supergravity* for theories linking all four forces.)

If these ideas are correct, then the universe was governed solely by the super force in the first instant after the Big Bang. As the universe expanded and cooled, the super force split into gravity and the GUT force, which then split further into the strong and electroweak forces. Ultimately, all four forces became distinct. As we'll see shortly, these changes in the fundamental forces probably occurred before the universe was one ten-billionth of a second old.

How did the early universe change with time?

The Big Bang theory uses scientific understanding of particles and forces to reconstruct the history of the universe. Here we will outline this history as a series of *eras*, or time periods. Each era is distinguished from the next by some major change in physical conditions as the universe cools. You'll find it useful to refer to the timeline shown in FIGURE 22.4 as you read along. Notice that the time scale in Figure 22.4 runs by powers of 10, which means that early eras were very brief, even though they appear spread out on the figure. It will take you longer to read this chapter than it took the universe to progress through the first five eras we will discuss, by which point the chemical composition of the early universe had already been determined.

The Planck Era The first era after the Big Bang is called the **Planck era**, named for physicist Max Planck; it represents times before the universe was 10^{-43} second old. Current theories cannot adequately describe the extreme conditions that must have existed during the Planck era. According to the laws of quantum mechanics, there must have been substantial energy fluctuations from point to point in the very early universe.



Planck Era
We lack a theory to describe conditions in the Planck era.

GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.

Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.

Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.

Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).

Era of Nuclei
A plasma of free electons and H and He nuclei filled the universe.

Era of Atoms
The era of atoms lasted until stars and galaxies began to form.

Gravity became distinct from other forces.

*The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called **inflation**.*

The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.

Protons annihilated virtually all antiprotons, but some protons remained.

Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.

Neutral atoms formed, allowing photons to travel freely through space.

FIGURE 22.4 **interactive figure** A timeline for the eras of the early universe. The only era not shown is the era of galaxies, which began with the birth of stars and galaxies when the universe was a few hundred million years old.

Because energy and mass are equivalent, Einstein's theory of general relativity tells us that these energy fluctuations must have generated a rapidly changing gravitational field that randomly warped space and time. During the Planck era, these fluctuations were so large that our current theories are inadequate to describe what might have been happening. The problem is that we do not yet have a theory that links quantum mechanics (our successful theory of the very small) and general relativity (our successful theory of the very big). Perhaps someday we will be able to merge these theories of the very small and the very big into a single "theory of everything" (see Special Topic, page 449). Until that happens, science cannot describe the universe during the Planck era.

Nevertheless, we have at least some idea of how the Planck era ended. If you look back at Figure 22.3, you'll see that all four forces are thought to merge into the single, unified super force at temperatures above 10^{32} K—the temperatures that prevailed during the Planck era. In that case, the Planck era would have been a time of ultimate simplicity, when just a single force operated in nature, and it came to an end when the temperature dropped low enough for gravity to become distinct from the other three forces, which were still merged as the GUT force. By analogy to the way ice crystals form as a liquid cools, we say that gravity "froze out" at the end of the Planck era.

The GUT Era The next era is called the **GUT era**, named for the grand unified theories (GUTs) that predict the merger of the strong, weak, and electromagnetic forces into a single GUT force at temperatures above 10^{29} K (see Figure 22.3). Although different grand unified theories disagree in many details, they all predict that the GUT era was a time during which two forces—gravity and the GUT force—operated in the universe. It came to an end when the GUT force split into the strong and electroweak forces, which happened when the universe was a mere 10^{-38} second old.

Our current understanding of physics allows us to say only slightly more about the GUT era than about the Planck era, and none of our ideas about the GUT era have been sufficiently tested to give us great confidence about what occurred during that time. However, if the grand unified theories are correct, the freezing out of the strong and electroweak forces may have released an enormous amount of energy, causing a sudden and dramatic expansion of the universe that we call **inflation**. In a mere 10^{-36} second, pieces of the universe the size of an atomic nucleus may have grown to the size of our solar system. Inflation sounds bizarre, but as we will discuss later, it explains several important features of today's universe.

The Electroweak Era The splitting of the GUT force marked the beginning of an era during which three distinct forces operated: gravity, the strong force, and the electroweak force. We call this time the **electroweak era**, indicating that the electromagnetic and weak forces were still merged together. Intense radiation continued to fill all of space, as it had since the Planck era, spontaneously producing matter and antimatter particles that almost immediately annihilated each other and turned back into photons.

The universe continued to expand and cool throughout the electroweak era, dropping to a temperature of 10^{15} K when it reached an age of 10^{-10} second. This temperature is still 100 million times hotter than the temperature in the core of the Sun today, but it was low enough for the electromagnetic and weak forces to freeze out from the electroweak force. After this instant (10^{-10} second), all four forces were forever distinct in the universe.

The end of the electroweak era marks an important transition not only in the physical universe, but also in human understanding of the universe. The theory that unified the weak and electromagnetic forces, which was developed in the 1970s, predicted the emergence of new types of particles (called the W and Z bosons, or *weak bosons*) at temperatures above the 10^{15} K temperature that pervaded the universe when it was 10^{-10} second old. In 1983, particle-accelerator experiments reached energies equivalent to such high temperatures for the first time. The new particles showed up just as predicted, produced from the extremely high energy in accord with $E = mc^2$. We therefore have direct experimental evidence concerning the conditions in the universe at the end of the electroweak era. We do *not* have any direct experimental evidence of conditions before that time. Our theories concerning the earlier parts of the electroweak era and the GUT era consequently are much more speculative than our theories describing the universe from the end of the electroweak era to the present.

The Particle Era As long as the universe was hot enough for the spontaneous creation and annihilation of particles to continue, the total number of particles was roughly in balance with the total number of photons. Once it became too cool for this spontaneous exchange of matter and energy to continue, photons became the dominant form of energy in the universe. We refer to the time between the end of the electroweak era and the moment when spontaneous particle production ceased as the **particle era**, to emphasize the importance of subatomic particles during this period.

During the early parts of the particle era (and during earlier eras), photons turned into all sorts of exotic particles that we no longer find freely existing in the universe today, including *quarks*—the building blocks of protons and neutrons [**Section S4.2**]. By the end of the particle era, all quarks had combined into protons and neutrons, which shared the universe with other particles such as electrons and neutrinos. The particle era came to an end when the universe reached an age of 1 millisecond (0.001 second) and the temperature had fallen to 10^{12} K. At this point, it was no longer hot enough to produce protons and antiprotons spontaneously from pure energy.

If the universe had contained equal numbers of protons and antiprotons (or neutrons and antineutrons) at the end of the particle era, all of the pairs would have annihilated each other, creating photons and leaving essentially no matter in the universe. From the obvious fact that the universe contains a significant amount of matter, we conclude that protons must have slightly outnumbered antiprotons at the end of the particle era.

We can of matter to antimatter by comparing the present numbers of protons and photons in the universe. These two numbers should have been similar in the very early universe, but today photons outnumber protons by about a billion to one. This ratio indicates that for every billion antiprotons in the early universe, there must have been about a billion and one protons. That is, for each 1 billion protons and antiprotons that annihilated each other at the end of the particle era, a single proton was left over. This seemingly slight excess of matter over antimatter makes up all the ordinary matter in the present-day universe. Some of those protons (and neutrons) left over from when the universe was 0.001 second old are the very ones that make up our bodies.

The Era of Nucleosynthesis The eras we have discussed so far all occurred within the first 0.001 second of the universe's existence—less time than it takes you to blink an eye. At this point, the protons and neutrons left over after the annihilation of antimatter began to fuse into heavier nuclei. However, the temperature of the universe remained so high that gamma rays blasted apart most of those nuclei as fast as they formed. This dance of fusion and demolition marked the **era of nucleosynthesis**, which ended when the universe was about 5 minutes old. By this time, the density in the expanding universe had dropped so much that fusion no longer occurred, even though the temperature was still about a billion Kelvin (10^9 K)—much hotter than the temperature of the Sun's core.

When fusion ceased at the end of the era of nucleosynthesis, the chemical content of the universe had become (by mass) about 75% hydrogen and 25% helium, along with trace amounts of deuterium (hydrogen with a neutron) and lithium (the next heaviest element after hydrogen and helium). Except for the small proportion of matter that stars later forged into heavier elements, the chemical composition of the universe remains the same today.

The Era of Nuclei After fusion ceased, the universe consisted of a very hot plasma of hydrogen nuclei, helium nuclei, and free electrons. This basic picture held for about the next 380,000 years as the universe continued to expand and cool. The fully ionized nuclei moved independently of electrons (rather than being bound with electrons in neutral atoms) during this period, which we call the **era of nuclei**. Throughout this era, photons bounced rapidly from one electron to the next, just as they do deep inside the Sun today [**Section 14.2**], never managing to travel far between collisions. Any time a nucleus managed to capture an electron to form a complete atom, one of the photons quickly ionized it.

The era of nuclei came to an end when the expanding universe was about 380,000 years old. At this point the temperature had fallen to about 3000 K—roughly half the temperature of the Sun's surface today. Hydrogen and helium nuclei finally captured electrons for good, forming stable, neutral atoms for the first time. With electrons now bound into atoms, the universe became transparent, as if a thick fog had suddenly lifted. Photons, formerly trapped among the electrons, began to stream freely across the universe. We still see these photons today as the *cosmic microwave background*, which we will discuss shortly.

The Era of Atoms We've already discussed the rest of the universe's history in earlier chapters. The end of the era of nuclei marked the beginning of the **era of atoms**, when the universe consisted of a mixture of neutral atoms and plasma (ions and electrons), along with a large number of photons. Because the density of matter in the universe differed slightly from place to place, gravity slowly drew atoms and plasma into the higher-density regions, which assembled into protogalactic clouds [**Section 21.1**]. Stars then formed in these clouds, and the clouds subsequently merged to form galaxies.

The Era of Galaxies The first full-fledged galaxies had formed by the time the universe was about 1 billion years old, beginning what we call the **era of galaxies**, which continues to this day. Generation after generation of star formation in galaxies steadily builds elements heavier than helium and incorporates them into new star systems. Some of these star systems develop planets, and on at least one of these planets life burst into being a few billion years ago. Now here we are, thinking about it all.

Early Universe Summary FIGURE 22.5 summarizes the major ideas from our brief overview of the history of the universe as it is described by the Big Bang theory. In the rest of this chapter, we will discuss the evidence that supports this theory. Before you read on, be sure to study the visual summary presented in Figure 22.5.

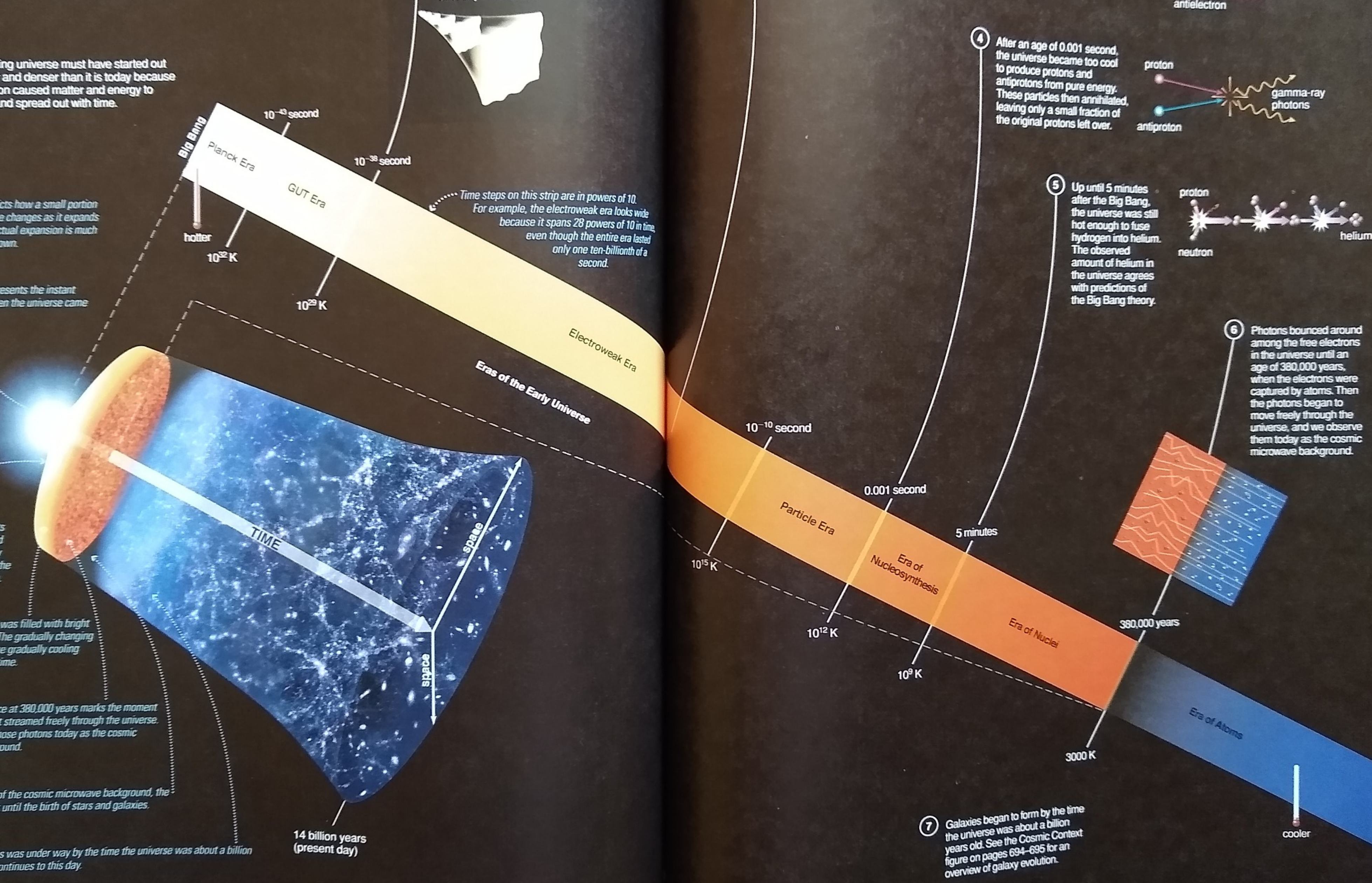
22.2 EVIDENCE FOR THE BIG BANG

What makes us think that a scientific theory can really describe events that occurred nearly 14 billion years ago? Like any scientific theory, the Big Bang theory is a model of nature designed to explain a set of observations. The model was inspired by Edwin Hubble's discovery of the universe's expansion: If the universe has been expanding for billions of years, then simple physical reasoning suggests that conditions ought to have been much denser and hotter in the past. However, the model was not accepted as a valid scientific theory until its major predictions were verified through additional observations and experiments. The Big Bang theory has gained wide scientific acceptance for two key reasons:

- It predicts that the radiation that began to stream across the universe at the end of the era of nuclei should still be present today. Sure enough, we find that the universe is filled with what we call the **cosmic microwave background**. Its characteristics precisely match what we expect according to the Big Bang model.
- It predicts that some of the original hydrogen in the universe should have fused into helium during the era of nucleosynthesis. Observations of the actual helium content of the universe closely match the amount of helium predicted by the Big Bang theory.

COSMIC CONTEXT FIGURE 22.5 The Early Universe

The Big Bang theory is a scientific model that explains how the present-day universe developed from an extremely hot and dense beginning. This schematic diagram shows how conditions in the early universe changed as the universe expanded and cooled with time.



① Our expanding universe must have started out much hotter and denser than it is today because the expansion caused matter and energy to cool down and spread out with time.

② As the universe cooled down, it may have undergone a brief period of very rapid expansion known as *inflation* that could account for several key properties of today's universe.

③ Temperatures shortly after the Big Bang were so hot that photons could change into elementary particles and vice versa. The early universe was therefore filled with photons and all kinds of elementary particles.

④ After an age of 0.001 second, the universe became too cool to produce protons and antiprotons from pure energy. These particles then annihilated, leaving only a small fraction of the original protons left over.

⑤ Up until 5 minutes after the Big Bang, the universe was still hot enough to fuse hydrogen into helium. The observed amount of helium in the universe agrees with predictions of the Big Bang theory.

⑥ Photons bounced around among the free electrons in the universe until an age of 380,000 years, when the electrons were captured by atoms. Then the photons began to move freely through the universe, and we observe them today as the cosmic microwave background.

⑦ Galaxies began to form by the time the universe was about a billion years old. See the Cosmic Context figure on pages 694–695 for an overview of galaxy evolution.

Time steps on this strip are in powers of 10. For example, the electroweak era looks wide because it spans 28 powers of 10 in time, even though the entire era lasted only one ten-billionth of a second.

This illustration depicts how a small portion of the entire universe changes as it expands with time, but the actual expansion is much greater than that shown.

This bright spot represents the instant of the Big Bang, when the universe came into existence.

This dramatic widening represents inflation—the rapid expansion that may have happened at the end of the GUT era.

The early universe was filled with bright light everywhere. The gradually changing color represents the gradually cooling temperature over time.

This blotchy surface at 380,000 years marks the moment when photons first streamed freely through the universe. We can still see those photons today as the cosmic microwave background.

After the release of the cosmic microwave background, the universe was dark until the birth of stars and galaxies.

The era of galaxies was under way by the time the universe was about a billion years old, and it continues to this day.

FIGURE 22.6 Arno Penzias and Robert Wilson, discoverers of the cosmic microwave background, with the Bell Labs microwave antenna.

Let's take a closer look at this evidence, starting with the cosmic microwave background.

How do observations of the cosmic microwave background support the Big Bang theory?

The discovery of the cosmic microwave background was announced in 1965. Arno Penzias and Robert Wilson, two physicists working at Bell Laboratories in New Jersey, were calibrating a sensitive microwave antenna designed for satellite communications (FIGURE 22.6). (*Microwaves* fall within the radio portion of the electromagnetic spectrum; see Figure 5.7.) Much to their chagrin, they kept finding unexpected "noise" in every measurement they made. The noise was the same no matter where they pointed the antenna, indicating that it came from all directions in the sky and ruling out any possibility that it came from any particular astronomical object or any place on Earth.

Meanwhile, physicists at nearby Princeton University were busy calculating the expected characteristics of the radiation left over from the heat of the Big Bang.* They concluded that, if the Big Bang had really occurred, this radiation should be permeating the entire universe and should be detectable with a microwave antenna. On a fateful airplane trip home from an astronomical meeting, Penzias sat next to an astronomer who told him of the Princeton calculations. The Princeton group soon met with Penzias and Wilson to compare notes, and both teams realized that the "noise" detected by the Bell Labs antenna was the predicted cosmic microwave background—the first strong evidence that the Big Bang had really happened. Penzias and Wilson received the 1978 Nobel Prize in physics for their discovery.

Origin of the Cosmic Microwave Background

The cosmic microwave background consists of microwave photons that have traveled through space since the end of the era of nuclei, when most of the electrons in the universe joined with nuclei to make neutral atoms, which interact less strongly with photons. With very few free electrons left to block them, most of the photons from that time have traveled unobstructed through the universe ever since (FIGURE 22.7). When we observe the cosmic microwave background, we essentially are seeing back to the end of the era of nuclei, when the universe was only 380,000 years old.

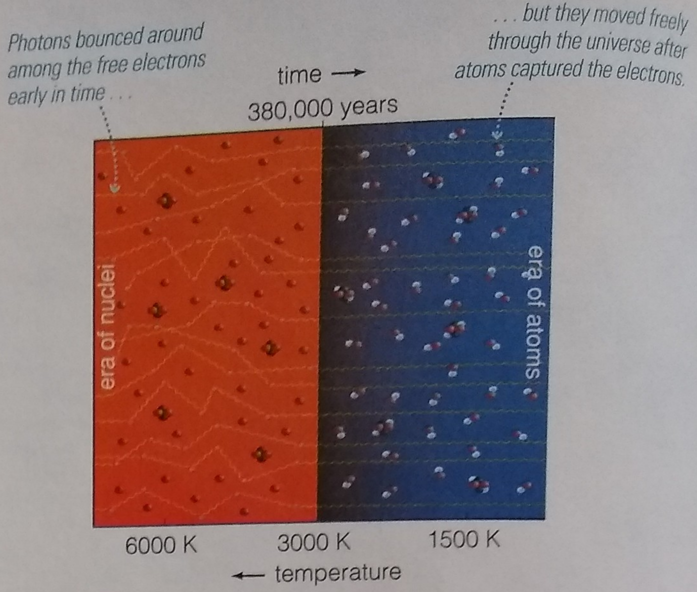


FIGURE 22.7 **interactive figure** Photons (yellow squiggles) frequently collided with free electrons during the era of nuclei and thus could travel freely only after electrons became bound into atoms. This transition was something like the transition from a dense fog to clear air. The photons released at the end of the era of nuclei, when the universe was about 380,000 years old, make up the cosmic microwave background. Precise measurements of these microwaves tell us what the universe was like at this moment in time.

Characteristics of the Cosmic Microwave Background The Big Bang theory predicts that the cosmic microwave background should have an essentially perfect thermal radiation spectrum [**Section 5.4**], because it came from the heat of the universe itself. Moreover, the theory predicts the approximate wavelength at which this thermal radiation spectrum should peak. As we discussed earlier, the theory tells us that the radiation of the cosmic microwave background broke free when the universe had cooled to a temperature of about 3000 K, similar to the surface temperature of a red giant star. The spectrum of the cosmic microwave background therefore should have originally peaked at a wavelength of about 1000 nanometers, just like the thermal radiation from a red star. Because the universe has since expanded by a factor of about 1000, the wavelengths of these photons should by now have stretched to about 1000 times their original wavelengths [**Section 20.3**]. We therefore expect the peak wavelength of the cosmic microwave background now to be about a millimeter, squarely in the microwave portion of the spectrum and corresponding to a temperature of a few degrees above absolute zero.

In the early 1990s, a NASA satellite called the *Cosmic Background Explorer (COBE)* was launched to test these ideas about the cosmic microwave background. The results

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*The possible existence of microwave radiation left over from the Big Bang was first predicted by George Gamow and his colleagues in the late 1940s, but neither Penzias and Wilson nor the Princeton group were aware of his work.

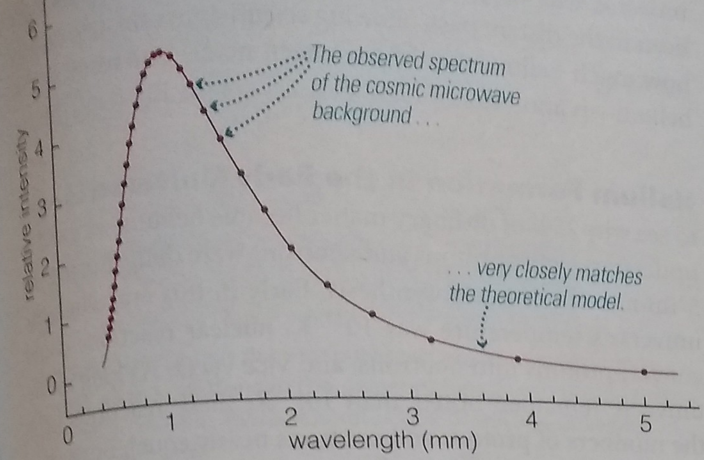

FIGURE 22.8 This graph shows the spectrum of the cosmic microwave background recorded by NASA's *COBE* satellite. A theoretically calculated thermal radiation spectrum (smooth curve) for a temperature of 2.73 K perfectly fits the data (dots). This excellent fit is important evidence in favor of the Big Bang theory.

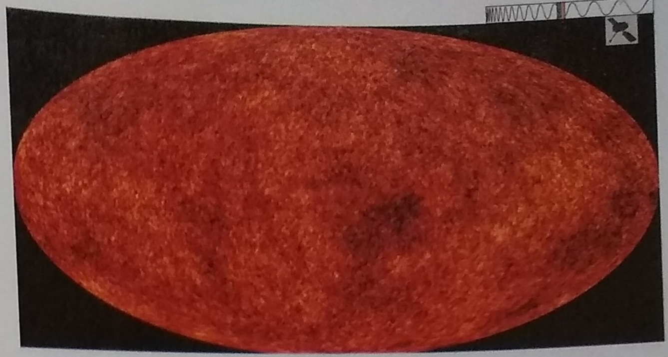

FIGURE 22.9 interactive photo This all-sky map shows temperature differences in the cosmic microwave background measured by *WMAP*. The background temperature is about 2.73 K everywhere, but the brighter regions of this picture are slightly less than 0.0001 K hotter than the darker regions—indicating that the early universe was very slightly lumpy at the end of the era of nuclei. We are essentially seeing what the universe was like at the surface marked "380,000 years" in Figure 22.5. Gravity later drew matter toward the centers of these lumps, forming the structures we see in the universe today.

were a stunning success for the Big Bang theory, and earned the 2006 Nobel Prize in physics for *COBE* team leaders George Smoot and John Mather. As shown in **FIGURE 22.8**, the cosmic microwave background does indeed have a perfect thermal radiation spectrum, with a peak corresponding to a temperature of 2.73 K.

THINK ABOUT IT

Suppose the cosmic microwave background did not really come from the heat of the universe itself but instead came from many individual stars and galaxies. Explain why, in that case, we would not expect it to have a perfect thermal radiation spectrum. How does the spectrum of the cosmic microwave background lend support to the Big Bang theory?

COBE and its successor missions, the *Wilkinson Microwave Anisotropy Probe (WMAP)* and the European *Planck* satellite, have also mapped the temperature of the cosmic microwave background in all directions (**FIGURE 22.9**). The temperature turns out to be extraordinarily uniform throughout the universe—just as the Big Bang theory predicts it should be—with variations from one place to another of only a few parts in 100,000.* Moreover, these slight variations also represent a predictive success of the Big Bang theory. Recall that our theory of galaxy formation depends on the assumption that the early universe was *not quite* perfectly uniform; some regions of the universe must have started out slightly denser than other regions, so that they could serve as seeds for galaxy formation [**Section 21.1**].

In fact, detailed observations of these small temperature variations are very important to studies of galaxy evolution, because all large structures in the universe are thought to have formed around the regions of slightly enhanced density [**Section 23.3**]. Measuring the patterns of variations in the cosmic microwave background therefore tells us both about what must have happened at even earlier times to create the variations and about the starting conditions that we should use in models of galaxy evolution.

SPECIAL TOPIC

The Steady State Universe

Although the Big Bang theory enjoys wide acceptance among scientists today, alternative ideas have been proposed and considered. One of the cleverest alternatives, developed in the late 1940s, was called the *steady state universe*. This hypothesis accepted the fact that the universe is expanding but rejected the idea of a Big Bang, instead postulating that the universe is infinitely old. The steady state hypothesis may seem paradoxical at first: If the universe has been expanding forever, shouldn't every galaxy be infinitely far away from every other galaxy? Proponents of the steady state universe answered by claiming that new galaxies continually form in the gaps that open up as the universe expands, thereby keeping the same average distance between galaxies at all times. In a sense, the steady state hypothesis said that the creation of the universe is an ongoing and eternal process rather than one that happened all at once with a Big Bang.

Two key discoveries caused the steady state hypothesis to lose favor. First, the 1965 discovery of the cosmic microwave background matched a prediction of the Big Bang theory but was not adequately explained by the steady state hypothesis. Second, a steady state universe should look about the same at all times, but observations made with increasingly powerful telescopes during the last half-century show that galaxies at great distances look younger than nearby galaxies. As a result of these predictive failures, most astronomers no longer take the steady state hypothesis seriously.

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*Earth's motion (such as our orbit around the Sun and the Sun's orbit around the center of the galaxy) means that we are moving relative to the cosmic microwave background radiation, causing a slight blueshift (about 0.12%) in the direction we're moving and a slight redshift in the opposite direction. Scientists must first subtract these effects before analyzing and making maps of the temperature of the background radiation.

How do the abundances of elements support the Big Bang theory?

The Big Bang theory also solves what had previously been another long-standing astronomical problem: the origin of cosmic helium. Everywhere in the universe, about three-quarters of the mass of ordinary matter (not including dark matter) is hydrogen and about one-quarter is helium. The Milky Way's helium fraction is about 28%, and no galaxy has a helium fraction lower than 25%. Although helium is produced by hydrogen fusion in stars, calculations show that this production can account for only a small proportion of the total observed helium. We therefore conclude that the majority of the helium in the universe must already have been present in the protogalactic clouds that preceded the formation of galaxies.

The Big Bang theory makes a specific prediction about the helium abundance. As we discussed earlier, the theory explains the existence of helium as a consequence of fusion that occurred during the era of nucleosynthesis, when the universe itself was hot enough to fuse hydrogen into helium. Combining the current microwave background temperature of 2.73 K with the number of protons we observe in the universe tells us precisely how hot the universe must have been in the distant past, allowing scientists to calculate exactly how much helium should have been made. The result—25% helium—is another impressive success of the Big Bang theory.

Helium Formation in the Early Universe In order to see why 25% of ordinary matter became helium, we need to understand what protons and neutrons were doing during the 5-minute era of nucleosynthesis. Early in this era, when the universe's temperature was 10^{11} K, nuclear reactions could convert protons into neutrons, and vice versa. As long as the universe remained hotter than 10^{11} K, these reactions kept the numbers of protons and neutrons nearly equal. But as the universe cooled, neutron-proton conversion reactions began to favor protons.

Neutrons are slightly more massive than protons, and therefore reactions that convert protons to neutrons require energy to proceed (in accordance with $E = mc^2$). As the temperature fell below 10^{11} K, the required energy for neutron production was no longer readily available, so the rate of these reactions slowed. In contrast, reactions that convert neutrons

MATHEMATICAL INSIGHT 22.1

Temperature and Wavelength of Background Radiation

Figure 22.8 shows that the cosmic microwave background has a nearly perfect thermal radiation spectrum for an object at a temperature of 2.73 K. Wien's law (see Mathematical Insight 5.2) therefore tells us that the wavelength of photons at the peak of the spectrum is

$$\lambda_{\text{max}} \approx \frac{2{,}900{,}000}{T\,(\text{Kelvin})}\,\text{nm} = \frac{2{,}900{,}000}{2.73}\,\text{nm} = 1.1 \times 10^6\,\text{nm}$$

Because 10^6 nm = 1 mm, this peak wavelength is equivalent to 1.1 millimeters. But what was the wavelength of the cosmic microwave photons in the past?

From Mathematical Insight 20.5, the universe has grown in size by a factor of $1 + z$ since the time light left objects that we observe to have a redshift z. Therefore, we find the peak wavelength of cosmic microwave photons at that time by dividing the current peak wavelength by $1 + z$:

$$\lambda_{\text{max}}\ (\text{at redshift } z) \approx \frac{1.1\ \text{mm}}{1 + z}$$

Combining this result with Wien's law and a little algebra, we find a simple formula for the temperature of the universe at any earlier time at which we see objects with redshift z:

$$T_{\text{universe}}\ (\text{at redshift } z) \approx 2.73\ \text{K} \times (1 + z)$$

EXAMPLE 1: Photons first moved freely when the universe had cooled to a temperature of about 3000 K. What was the peak wavelength of the photons at that time?

SOLUTION:

Step 1 Understand: We can simply use Wien's law relating peak wavelength to temperature.

Step 2 Solve: We use the temperature of 3000 K in Wien's law:

$$\lambda_{\text{max}} \approx \frac{2{,}900{,}000}{T\,(\text{Kelvin})}\,\text{nm} = \frac{2{,}900{,}000}{3000}\,\text{nm} = 970\ \text{nm}$$

Step 3 Explain: The peak wavelength of the photons when they first began to travel freely was about 970 nanometers, which is in the infrared portion of the electromagnetic spectrum fairly close to the wavelength of red visible light (see Figure 5.7).

EXAMPLE 2: How much has the expansion of the universe stretched the wavelengths of the background radiation since it began to travel freely through the universe?

SOLUTION:

Step 1 Understand: We can use the formula that relates the temperature of the background radiation to the cosmological redshift z. We are given the 3000 K temperature, so we need to find the stretching factor $(1 + z)$.

Step 2 Solve: We divide both sides of the earlier equation by the current temperature of the universe, 2.73 K, to find

$$1 + z = \frac{T_{\text{universe}}\ (\text{at redshift } z)}{2.73\ \text{K}}$$

In this case, we are looking for the stretching factor corresponding to the time when the universe had a temperature of 3000 K. Plugging this value into the formula, we find

$$1 + z = \frac{3000\ \text{K}}{2.73\ \text{K}} \approx 1100$$

Step 3 Explain: The expansion of the universe has stretched photons by a factor of about 1100 since the time they first began to travel freely across the universe, when the universe was about 380,000 years old. (The answer has no units because it is the *ratio* of the size of the universe now to the size of the universe then.)

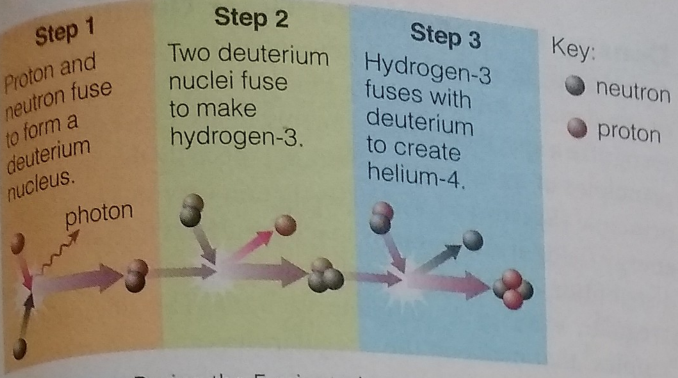

FIGURE 22.10 During the 5-minute-long era of nucleosynthesis, virtually all the neutrons in the universe fused with protons to form helium-4. This figure illustrates one of several possible reaction pathways.

into protons release energy and therefore are unhindered by cooler temperatures. By the time the temperature of the universe fell to 10^{10} K, protons had begun to outnumber neutrons because the conversion reactions ran only in one direction. Neutrons changed into protons, but the protons didn't change back.

For the next few minutes, the universe was still hot and dense enough for nuclear fusion to take place. Protons and neutrons constantly combined to form *deuterium*—the rare form of hydrogen that contains a neutron in addition to a proton in the nucleus—and deuterium nuclei fused to form helium (**FIGURE 22.10**). However, during the early part of the era of nucleosynthesis, the helium nuclei were almost immediately blasted apart by one of the many gamma rays that filled the universe.

Fusion began to create long-lasting helium nuclei when the universe was about 1 minute old and had cooled to a temperature at which it contained few destructive gamma rays. Calculations show that the proton-to-neutron ratio at this time should have been about 7 to 1. Moreover, almost all the available neutrons should have been incorporated into nuclei of helium-4.

FIGURE 22.11 shows that, based on the 7-to-1 ratio of protons to neutrons, the universe should have had a composition of 75% hydrogen and 25% helium by mass at the end of the era of nucleosynthesis. This match between the predicted and observed helium ratios provides strong support to the Big Bang theory.

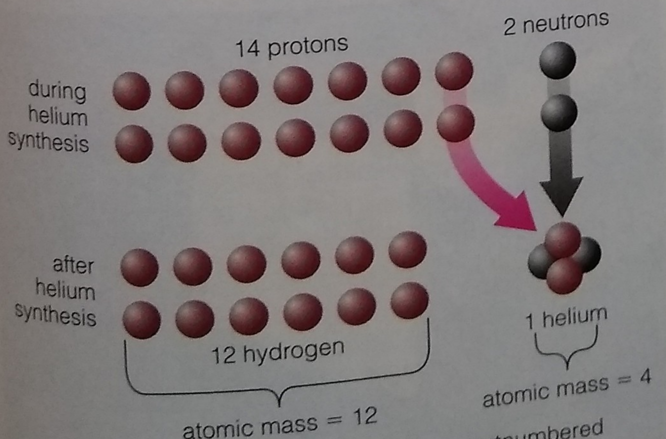

FIGURE 22.11 Calculations show that protons outnumbered neutrons 7 to 1, which is the same as 14 to 2, during the era of nucleosynthesis. The result was 12 hydrogen nuclei (individual protons) for each helium nucleus. Therefore, the predicted hydrogen-to-helium mass ratio is 12 to 4, which is the same as 75% to 25%, in agreement with the observed abundance of helium.

THINK ABOUT IT

Briefly explain why it should not be surprising that some galaxies contain a little more than 25% helium, but why it would be very surprising if some galaxies contained less. (*Hint:* Think about how the relative amounts of hydrogen and helium in the universe are affected by fusion in stars.)

Abundances of Other Light Elements Why didn't the Big Bang produce heavier elements? By the time stable helium nuclei formed, when the universe was about a minute old, the temperature and density of the rapidly expanding universe had already dropped too far for a process like carbon production (three helium nuclei fusing into carbon [**Section 17.2**]) to occur. Reactions between protons, deuterium nuclei, and helium were still possible, but most of these reactions led nowhere. In particular, fusing two helium-4 nuclei results in a nucleus that is unstable and falls apart in a fraction of a second, as does fusing a proton to a helium-4 nucleus.

A few reactions involving hydrogen-3 (also known as *tritium*) or helium-3 can create long-lasting nuclei. For example, fusing helium-4 and hydrogen-3 produces lithium-7. However, the contributions of these reactions to the overall composition of the universe were minor because hydrogen-3 and helium-3 were so rare. Models of element production in the early universe show that, before the cooling of the universe shut off fusion entirely, such reactions generated only trace amounts of lithium, the next heavier element after helium. Aside from hydrogen, helium, and lithium, all other elements were forged much later in the nuclear furnaces of stars. (Beryllium and boron, which are heavier than lithium but lighter than carbon, were created later when high-energy particles broke apart heavier nuclei that formed in stars.)

22.3 THE BIG BANG AND INFLATION

When we discussed the eras of the universe earlier in the chapter, we noted that the universe is thought to have undergone a sudden and dramatic expansion, called *inflation*, which may have occurred at the end of the GUT era, when the universe was 10^{-38} second old.[*] This idea first emerged in 1981, when physicist Alan Guth was considering the consequences of the separation of the strong force from the GUT force that marked the end of the GUT era. Some theories of high-energy physics predict that this separation of forces

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[*] In some models of inflation, the dramatic expansion can happen later, up until the end of the electroweak era.