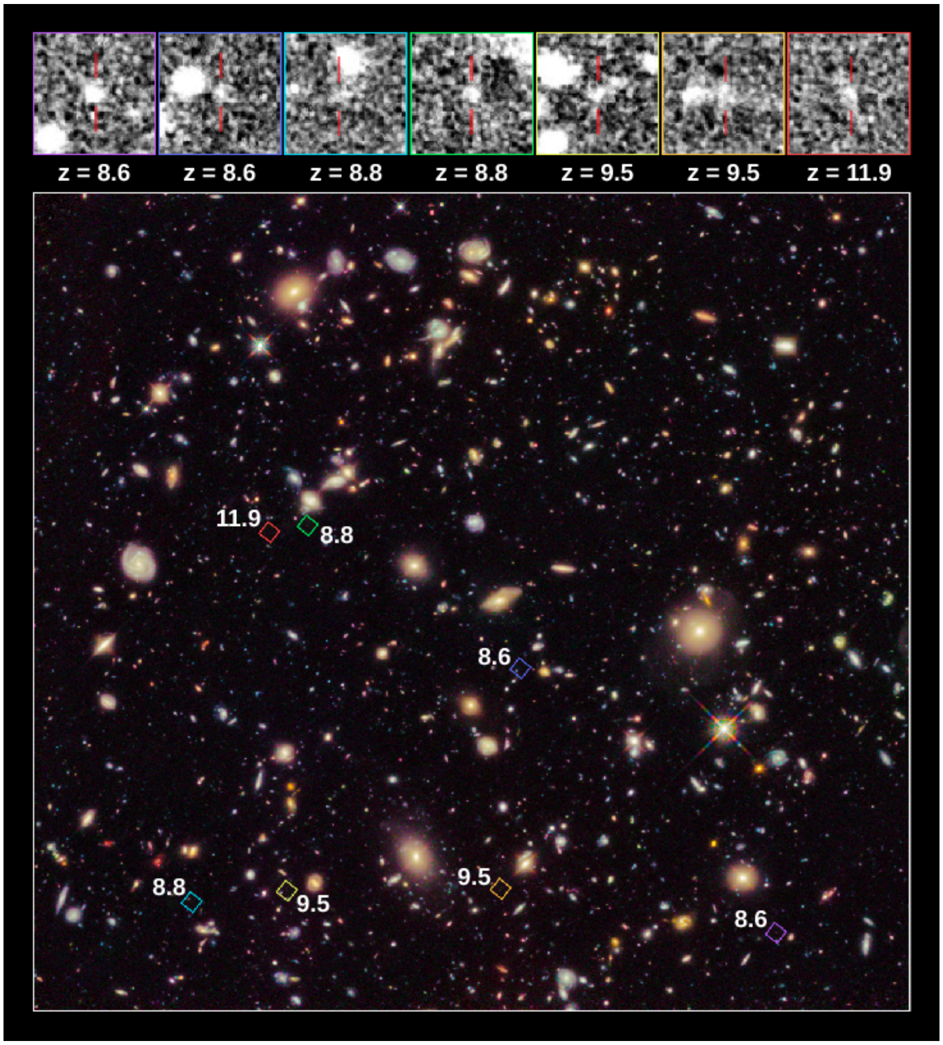

Figure 29.10 Hubble Ultra-Deep Field. This image, called the Hubble Ultra Deep Field, shows faint galaxies, seen very far away and therefore very far back in time. The colored squares in the main image outline the locations of the galaxies. Enlarged views of each galaxy are shown in the black-and-white images. The red lines mark each galaxy's location. The "redshift" of each galaxy is indicated below each box, denoted by the symbol "z." The redshift measures how much a galaxy's ultraviolet and visible light has been stretched to infrared wavelengths by the universe's expansion. The larger the redshift, the more distant the galaxy, and therefore the further astronomers are seeing back in time. One of the seven galaxies may be a distance breaker, observed at a redshift of 11.9. If this redshift is confirmed by additional measurements, the galaxy is seen as it appeared only 380 million years after the Big Bang, when the universe was less than 3% of its present age. (credit: modification of work by NASA, ESA, R. Ellis (Caltech), and the UDF 2012 Team)

29.3 The Beginning of the Universe

Learning Objectives

By the end of this section, you will be able to:

- Describe what the universe was like during the first few minutes after it began to expand
- Explain how the first new elements were formed during the first few minutes after the Big Bang
- Describe how the contents of the universe change as the temperature of the universe decreases

The best evidence we have today indicates that the first galaxies did not begin to form until a few hundred million years after the Big Bang. What were things like before there were galaxies and space had not yet stretched very significantly? Amazingly, scientists have been able to calculate in some detail what was happening in the universe in the first few minutes after the Big Bang.

The History of the Idea

It is one thing to say the universe had a beginning (as the equations of general relativity imply) and quite another to describe that beginning. The Belgian priest and cosmologist Georges Lemaître was probably the first to propose a specific model for the Big Bang itself (Figure 29.11). He envisioned all the matter of the universe starting in one great bulk he called the *primeval atom*, which then broke into tremendous numbers of pieces. Each of these pieces continued to fragment further until they became the present atoms of the universe, created in a vast nuclear fission. In a popular account of his theory, Lemaître wrote, “The evolution of the world could be compared to a display of fireworks just ended—some few red wisps, ashes, and smoke. Standing on a well-cooled cinder, we see the slow fading of the suns and we try to recall the vanished brilliance of the origin of the worlds.”

Figure 29.11 Abbé Georges Lemaître (1894–1966). This Belgian cosmologist studied theology at Mechelen and mathematics and physics at the University of Leuven. It was there that he began to explore the expansion of the universe and postulated its explosive beginning. He actually predicted Hubble’s law 2 years before its verification, and he was the first to consider seriously the physical processes by which the universe began.

LINK TO LEARNING

View a short video (https://openstax.org/l/30Lemaitrevid) about the work of Lemaître, considered by some to be the father of the Big Bang theory.

Physicists today know much more about nuclear physics than was known in the 1920s, and they have shown that the primeval fission model cannot be correct. Yet Lemaître’s vision was in some respects quite prophetic. We still believe that everything was together at the beginning; it was just not in the form of matter we now know. Basic physical principles tell us that when the universe was much denser, it was also much hotter, and that it cools as it expands, much as gas cools when sprayed from an aerosol can.

By the 1940s, scientists knew that fusion of hydrogen into helium was the source of the Sun’s energy. Fusion requires high temperatures, and the early universe must have been hot. Based on these ideas, American physicist George Gamow (Figure 29.12) suggested a universe with a different kind of beginning that involved nuclear **fusion** instead of fission. Ralph Alpher worked out the details for his PhD thesis, and the results were published in 1948. (Gamow, who had a quirky sense of humor, decided at the last minute to add the name of physicist Hans Bethe to their paper, so that the coauthors on this paper about the beginning of things would be Alpher, Bethe, and Gamow, a pun on the first three letters of the Greek alphabet: alpha, beta, and gamma.)

Gamow’s universe started with fundamental particles that built up the heavy elements by fusion in the Big Bang.

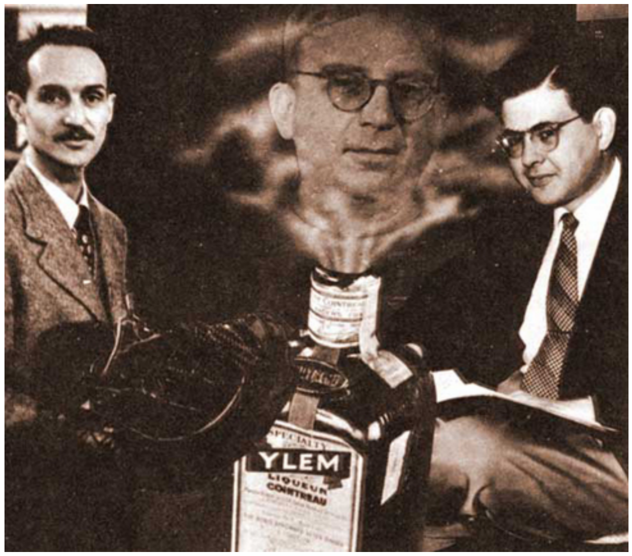

Figure 29.12 George Gamow and Collaborators. This composite image shows George Gamow emerging like a genie from a bottle of ylem, a Greek term for the original substance from which the world formed. Gamow revived the term to describe the material of the hot Big Bang. Flanking him are Robert Herman (left) and Ralph Alpher (right), with whom he collaborated in working out the physics of the Big Bang. (The modern composer Karlheinz Stockhausen was inspired by Gamow’s ideas to write a piece of music called *Ylem*, in which the players actually move away from the stage as they perform, simulating the expansion of the universe.)

Gamow’s ideas were close to our modern view, except we now know that the early universe remained hot enough for fusion for only a short while. Thus, only the three lightest elements—hydrogen, helium, and a small amount of lithium—were formed in appreciable abundances at the beginning. The heavier elements formed later in stars. Since the 1940s, many astronomers and physicists have worked on a detailed theory of what happened in the early stages of the universe.

The First Few Minutes

Let’s start with the first few minutes following the Big Bang. Three basic ideas hold the key to tracing the changes that occurred during the time just after the universe began. The first, as we have already mentioned, is that the universe cools as it expands. Figure 29.13 shows how the temperature changes with the passage of time. Note that a huge span of time, from a tiny fraction of a second to billions of years, is summarized in this diagram. In the first fraction of a second, the universe was unimaginably hot. By the time 0.01 second had elapsed, the temperature had dropped to 100 billion (10^{11}) K. After about 3 minutes, it had fallen to about 1 billion (10^9) K, still some 70 times hotter than the interior of the Sun. After a few hundred thousand years, the temperature was down to a mere 3000 K, and the universe has continued to cool since that time.

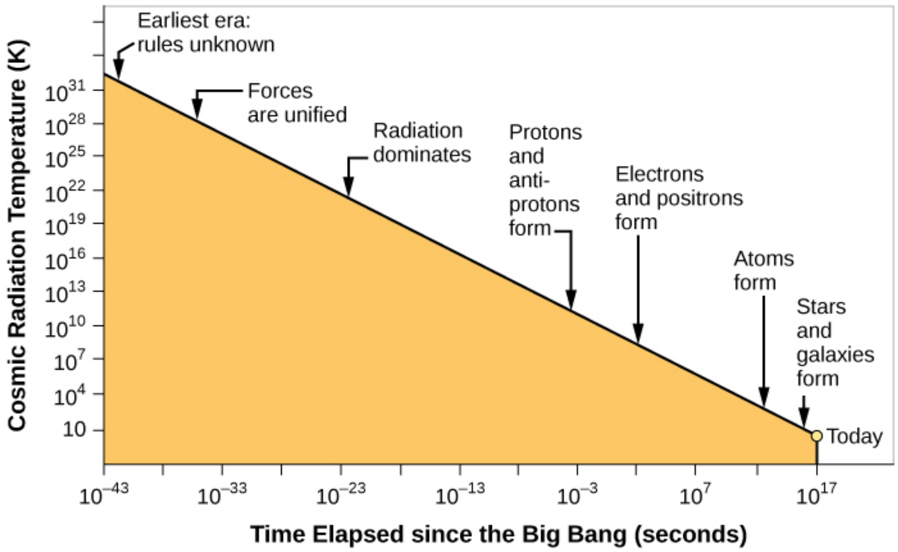

Figure 29.13 Temperature of the Universe. This graph shows how the temperature of the universe varies with time as predicted by the standard model of the Big Bang. Note that both the temperature (vertical axis) and the time in seconds (horizontal axis) change over vast scales on this compressed diagram.

All of these temperatures but the last are derived from theoretical calculations since (obviously) no one was there to measure them directly. As we shall see in the next section, however, we have actually detected the feeble glow of radiation emitted at a time when the universe was a few hundred thousand years old. We can measure the characteristics of that radiation to learn what things were like long ago. Indeed, the fact that we have found this ancient glow is one of the strongest arguments in favor of the Big Bang model.

The second step in understanding the evolution of the universe is to realize that at very early times, it was so hot that it contained mostly radiation (and not the matter that we see today). The photons that filled the universe could collide and produce material particles; that is, under the conditions just after the Big Bang, energy could turn into matter (and matter could turn into energy). We can calculate how much mass is produced from a given amount of energy by using Einstein's formula $E = mc^2$ (see the chapter on The Sun: A Nuclear Powerhouse).

The idea that energy could turn into matter in the universe at large is a new one for many students, since it is not part of our everyday experience. That's because, when we compare the universe today to what it was like right after the Big Bang, we live in cold, hard times. The photons in the universe today typically have far-less energy than the amount required to make new matter. In the discussion on the source of the Sun's energy in The Sun: A Nuclear Powerhouse, we briefly mentioned that when subatomic particles of matter and *antimatter* collide, they turn into pure energy. But the reverse, energy turning into matter and antimatter, is equally possible. This process has been observed in particle accelerators around the world. If we have enough energy, under the right circumstances, new particles of matter (and antimatter) are indeed created —and the conditions were right during the first few minutes after the expansion of the universe began.

Our third key point is that the hotter the universe was, the more energetic were the photons available to make matter and antimatter (see Figure 29.13). To take a specific example, at a temperature of 6 billion (6×10^9) K, the collision of two typical photons can create an electron and its antimatter counterpart, a positron. If the temperature exceeds 10^{14} K, much more massive protons and antiprotons can be created.

The Evolution of the Early Universe

Keeping these three ideas in mind, we can trace the evolution of the universe from the time it was about 0.01 second old and had a temperature of about 100 billion K. Why not begin at the very beginning? There are as yet no theories that allow us penetrate to a time before about 10^{-43} second (this number is a decimal point followed by 42 zeros and then a one). It is so small that we cannot relate it to anything in our everyday experience. When the universe was that young, its density was so high that the theory of general relativity is not adequate to describe it, and even the concept of time breaks down.

Scientists, by the way, have been somewhat more successful in describing the universe when it was older than $10^{–43}$ second but still less than about 0.01 second old. We will take a look at some of these ideas later in this chapter, but for now, we want to start with somewhat more familiar situations.

By the time the universe was 0.01 second old, it consisted of a soup of matter and radiation; the matter included protons and neutrons, leftovers from an even younger and hotter universe. Each particle collided rapidly with other particles. The temperature was no longer high enough to allow colliding photons to produce neutrons or protons, but it was sufficient for the production of electrons and positrons (Figure 29.14). There was probably also a sea of exotic subatomic particles that would later play a role as dark matter. All the particles jiggled about on their own; it was still much too hot for protons and neutrons to combine to form the nuclei of atoms.

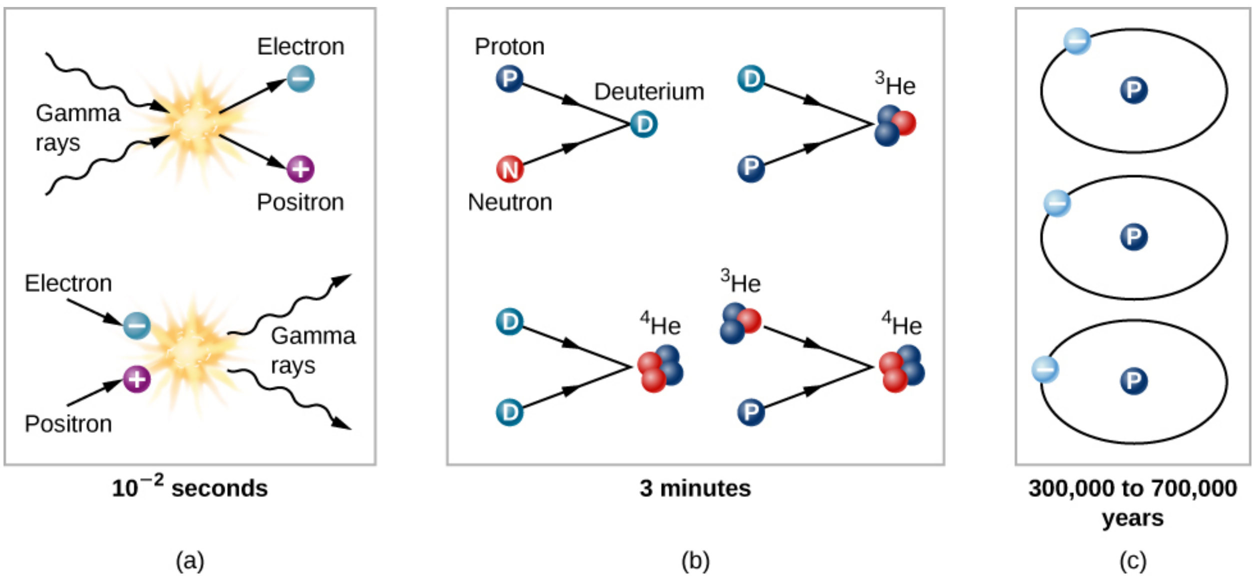

Figure 29.14 Particle Interactions in the Early Universe. (a) In the first fractions of a second, when the universe was very hot, energy was converted into particles and antiparticles. The reverse reaction also happened: a particle and antiparticle could collide and produce energy. (b) As the temperature of the universe decreased, the energy of typical photons became too low to create matter. Instead, existing particles fused to create such nuclei as deuterium and helium. (c) Later, it became cool enough for electrons to settle down with nuclei and make neutral atoms. Most of the universe was still hydrogen.

Think of the universe at this time as a seething cauldron, with photons colliding and interchanging energy, and sometimes being destroyed to create a pair of particles. The particles also collided with one another. Frequently, a matter particle and an antimatter particle met and turned each other into a burst of gamma-ray radiation.

Among the particles created in the early phases of the universe was the ghostly neutrino (see The Sun: A Nuclear Powerhouse), which today interacts only very rarely with ordinary matter. In the crowded conditions of the very early universe, however, neutrinos ran into so many electrons and positrons that they experienced frequent interactions despite their “antisocial” natures.

By the time the universe was a little more than 1 second old, the density had dropped to the point where neutrinos no longer interacted with matter but simply traveled freely through space. In fact, these neutrinos should now be all around us. Since they have been traveling through space unimpeded (and hence unchanged) since the universe was 1 second old, measurements of their properties would offer one of the best tests of the Big Bang model. Unfortunately, the very characteristic that makes them so useful—the fact that they interact so weakly with matter that they have survived unaltered for all but the first second of time—also renders them unable to be measured, at least with present techniques. Perhaps someday someone will devise a way to capture these elusive messengers from the past.

Atomic Nuclei Form

When the universe was about 3 minutes old and its temperature was down to about 900 million K, protons and neutrons could combine. At higher temperatures, these atomic nuclei had immediately been blasted apart by interactions with high-energy photons and thus could not survive. But at the temperatures and densities reached between 3 and 4 minutes after the beginning, **deuterium** (a proton and neutron) lasted long enough that collisions could convert some of it into helium, (Figure 29.14). In essence, the entire universe was acting the way centers of stars do today—fusing new elements from simpler components. In addition, a little bit of element 3, **lithium**, could also form.

This burst of cosmic fusion was only a brief interlude, however. By 4 minutes after the Big Bang, more helium was having trouble forming. The universe was still expanding and cooling down. After the formation of helium and some lithium, the temperature had dropped so low that the fusion of helium nuclei into still-heavier elements could not occur. No elements beyond lithium could form in the first few minutes. That 4-minute period was the end of the time when the entire universe was a fusion factory. In the cool universe we know today, the fusion of new elements is limited to the centers of stars and the explosions of supernovae.

Still, the fact that the Big Bang model allows the creation of a good deal of helium is the answer to a long-standing mystery in astronomy. Put simply, there is just too much helium in the universe to be explained by what happens inside stars. All the generations of stars that have produced helium since the Big Bang cannot account for the quantity of helium we observe. Furthermore, even the oldest stars and the most distant galaxies show significant amounts of helium. These observations find a natural explanation in the synthesis of helium by the Big Bang itself during the first few minutes of time. We estimate that *10 times more helium* was manufactured in the first 4 minutes of the universe than in all the generations of stars during the succeeding 10 to 15 billion years.

Learning from Deuterium

We can learn many things from the way the early universe made atomic nuclei. It turns out that all of the deuterium (a hydrogen nucleus with a neutron in it) in the universe was formed during the first 4 minutes. In stars, any region hot enough to fuse two protons to form a deuterium nucleus is also hot enough to change it further—either by destroying it through a collision with an energetic photon or by converting it into helium through nuclear reactions.

The amount of deuterium that can be produced in the first 4 minutes of creation depends on the density of the universe at the time deuterium was formed. If the density were relatively high, nearly all the deuterium would have been converted into helium through interactions with protons, just as it is in stars. If the density were relatively low, then the universe would have expanded and thinned out rapidly enough that some deuterium would have survived. The amount of deuterium we see today thus gives us a clue to the density of the universe when it was about 4 minutes old. Theoretical models can relate the density then to the density now; thus, measurements of the abundance of deuterium today can give us an estimate of the current density of the universe.

The measurements of deuterium indicate that the present-day density of ordinary matter—protons and neutrons—is about 5×10^{-28} kg/m^3. Deuterium can only provide an estimate of the density of ordinary matter because the abundance of deuterium is determined by the particles that interact to form it, namely protons and neutrons alone. From the abundance of deuterium, we know that not enough protons and neutrons are present, by a factor of about 20, to produce a critical-density universe.

We do know, however, that there are dark matter particles that add to the overall matter density of the universe, which is then higher than what is calculated for ordinary matter alone. Because dark matter particles do not affect the production of deuterium, measurement of the deuterium abundance cannot tell us how much dark matter exists. Dark matter is made of some exotic kind of particle, not yet detected in any earthbound laboratory. It is definitely not made of protons and neutrons like the readers of this book.

29.4 The Cosmic Microwave Background

Learning Objectives

By the end of this section, you will be able to:

- Explain why we can observe the afterglow of the hot, early universe
- Discuss the properties of this afterglow as we see it today, including its average temperature and the size of its temperature fluctuations
- Describe open, flat, and curved universes and explain which type of universe is supported by observations
- Summarize our current knowledge of the basic properties of the universe including its age and contents

The description of the first few minutes of the universe is based on theoretical calculations. It is crucial, however, that a scientific theory should be testable. What predictions does it make? And do observations show those predictions to be accurate? One success of the theory of the first few minutes of the universe is the correct prediction of the amount of helium in the universe.

Another prediction is that a significant milestone in the history of the universe occurred about 380,000 years after the Big Bang. Scientists have directly observed what the universe was like at this early stage, and these observations offer some of the strongest support for the Big Bang theory. To find out what this milestone was, let’s look at what theory tells us about what happened during the first few hundred thousand years after the Big Bang.

The fusion of helium and lithium was completed when the universe was about 4 minutes old. The universe then continued to resemble the interior of a star in some ways for a few hundred thousand years more. It remained hot and opaque, with radiation being scattered from one particle to another. It was still too hot for electrons to “settle down” and become associated with a particular nucleus; such free electrons are especially effective at scattering photons, thus ensuring that no radiation ever got very far in the early universe without having its path changed. In a way, the universe was like an enormous crowd right after a popular concert; if you get separated from a friend, even if he is wearing a flashing button, it is impossible to see through the dense crowd to spot him. Only after the crowd clears is there a path for the light from his button to reach you.

The Universe Becomes Transparent

Not until a few hundred thousand years after the Big Bang, when the temperature had dropped to about 3000 K and the density of atomic nuclei to about 1000 per cubic centimeter, did the electrons and nuclei manage to combine to form stable atoms of hydrogen and helium (Figure 29.14). With no free electrons to scatter photons, the universe became transparent for the first time in cosmic history. From this point on, matter and radiation interacted much less frequently; we say that they *decoupled* from each other and evolved separately. Suddenly, electromagnetic radiation could really travel, and it has been traveling through the universe ever since.

Discovery of the Cosmic Background Radiation

If the model of the universe described in the previous section is correct, then—as we look far outward in the universe and thus far back in time—the first “afterglow” of the hot, early universe should still be detectable. Observations of it would be very strong evidence that our theoretical calculations about how the universe evolved are correct. As we shall see, we have indeed detected the radiation emitted at this **photon decoupling time**, when radiation began to stream freely through the universe without interacting with matter (Figure 29.15).