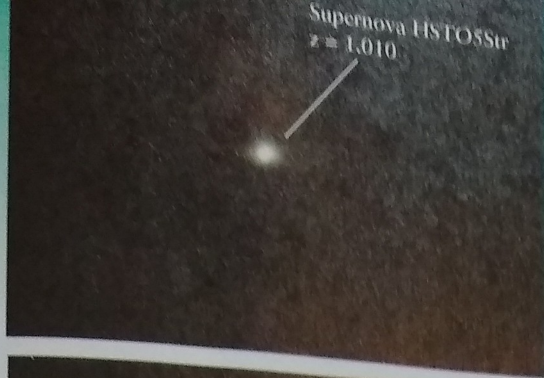
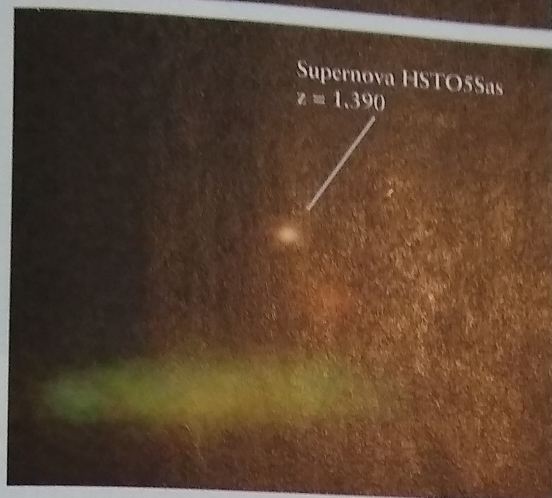
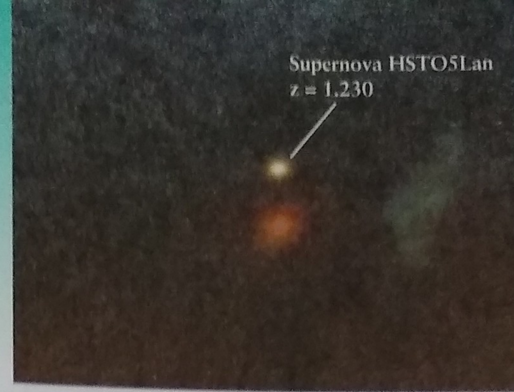






Very distant supernovae—which we see as they were billions of years ago—help us understand the evolution of the universe. (NASA; ESA; and A. Riess, STScI)

R I V U X G

CHAPTER 25

Cosmology: The Origin and Evolution of the Universe

LEARNING GOALS

By reading the sections of this chapter, you will learn

25-1 Why the darkness of the night sky presents a mystery

25-2 What it means to say that the universe is expanding

25-3 How to estimate the age of the universe from its expansion rate

25-4 How astronomers detect the afterglow of the Big Bang

25-5 What the universe was like during its first 380,000 years

25-6 How the curvature of the universe reveals its matter and energy content

25-7 What distant supernovae tell us about the expansion history of the universe

25-8 How cosmic sound waves reveal details of our universe

So far in this book we have cataloged the contents of the universe. Our scope has ranged from subatomic objects to superclusters of galaxies hundreds of millions of light-years across. In between, we have studied planets, moons, and stars.

But now we turn our focus beyond the objects we find in the universe to the nature of the universe itself—the subject of the science called *cosmology.* How large is the universe? What is its structure? How long has it existed, and how has it changed over time?

In this chapter we will see that the universe is expanding. This expansion began with an event at the beginning of time called the *Big Bang.* We will see direct evidence of the Big Bang in the form of microwave radiation from space. This radiation is the faint afterglow of a primordial fireball that filled all space shortly after the beginning of the universe.

Will the universe continue to expand forever, or will it eventually collapse back on itself? We will find that to predict the future of the universe, we must first understand what happened in the remote past. To this end, astronomers study luminous supernovae like the example shown in the above images. These can be seen across billions of light-years and so can tell us about conditions in the universe billions of years ago. We will see how recent results from such supernovae, as well as from studies of the Big Bang's afterglow, have revolutionized our understanding of cosmology and given us new insights into our place in the cosmos.

25-1 The darkness of the night sky tells us about the nature of the universe

Cosmology is the science concerned with the structure and evolution of the universe as a whole. One of the most profound and basic questions in cosmology may at first seem foolish: Why is the sky dark at night? This question, which haunted Johannes Kepler as long ago as 1610, was brought to public attention in the early 1800s by the German amateur astronomer Heinrich Olbers.

Olbers' Paradox and Newton's Static Universe

Olbers and his contemporaries pictured a universe of stars scattered more or less randomly throughout infinite space. Isaac Newton himself thought that no other model made sense. The gravitational forces between any *finite* number of stars, he argued, would in time cause them all to fall together, and the universe would soon be a compact blob.

Obviously, this has not happened. Newton concluded that we must be living amid a static, infinite expanse of stars. In this model, the universe is infinitely old, and it will exist forever without major changes in its structure. Olbers noticed, however, that a static, infinite universe presents a major puzzle.

If space goes on forever, with stars scattered throughout it, then any line of sight must eventually hit a star. In this case, no matter where you look in the night sky, you should ultimately see a star. The entire sky should be as bright as an average star, so, even at night, the sky should blaze like the surface of the Sun. **Olbers's paradox** is that the night sky is actually *dark* (Figure 25-1).

FIGURE 25-1 R I V U X G
The Dark Night Sky If the universe were infinitely old and filled uniformly with stars that were fixed in place, the night sky would be ablaze with light. In fact the night sky is dark, punctuated only by the light from isolated stars and galaxies. Hence, this simple picture of an infinite, static universe cannot be correct. (NASA; ESA; and the Hubble Heritage Team, STScI/AURA)

Olbers's paradox suggests that something is wrong with Newton's infinite, static universe. According to the classical, Newtonian picture of reality, space is like a gigantic flat sheet of inflexible, rectangular graph paper. (Space is actually three-dimensional, but it is easier to visualize just two of its three dimensions. In a similar way, an ordinary map represents the three-dimensional surface of Earth, with its hills and valleys, as a flat, two-dimensional surface.)

This rigid, flat, Newtonian space extends unchanged, on and on, totally independent of stars or galaxies or anything else. The same is true of time in Newton's view of the universe; a Newtonian clock ticks steadily and monotonously forever, never slowing down or speeding up. Furthermore, Newtonian space and time are unrelated, in that a clock runs at the same rate no matter where in the universe it is located.

Einstein's Revolution and His "Greatest Blunder"

Albert Einstein overturned this view of space and time. His special theory of relativity (recall Section 21-1 and Box 21-1) shows that measurements with clocks and rulers depend on the motion of the observer. What is more, Einstein's general theory of relativity (Section 21-2) tells us that gravity curves the fabric of space. As a result, just as one massive object can bend the space around it, the matter that occupies the universe influences the overall shape of space throughout the universe.

If we represent the universe as a sheet of graph paper, the sheet is not perfectly flat but has a dip wherever there is a concentration of mass, such as a person, a planet, or a star (see Figure 21-4). Also, because of gravitational effects, clocks run at different rates depending on whether they are close to or far from a massive object, as Figure 21-7a shows.

What does the general theory of relativity, with its many differences from the Newtonian picture, have to say about the structure of the universe as a whole? Einstein attacked this problem shortly after formulating his general theory in 1915. At that time, the prevailing view was that the universe was static, just as Newton had thought.

Einstein narrowly missed predicting that our universe is not static

Einstein was therefore dismayed to find that his calculations could not produce a truly static universe. According to general relativity, the universe must be either expanding or contracting. In a desperate move to force his theory to predict a static universe, he added to the equations of general relativity a term called the **cosmological constant** (denoted by Λ, the capital Greek letter lambda). The cosmological constant was intended to represent a pressure that tends to make the universe expand as a whole. Einstein's idea was that this pressure would just exactly balance gravitational attraction, so that the universe would be static and not collapse.

ANALOGY Einstein's cosmological constant is analogous to the pressure of gas inside a balloon once the balloon has already been inflated. This pressure exactly balances the inward force exerted by the stretched rubber of the balloon itself, so the balloon maintains the same size.

Unlike other aspects of Einstein's theories, the cosmological constant did not have a firm basis in physics. He just added it to make the general theory of relativity agree with the prejudice that the universe is static.

Because Einstein doubted his original equations, he missed an incredible opportunity: He could have postulated that we live in an expanding universe. Einstein has been quoted as saying in his later years that the cosmological constant was "the greatest blunder of my life." (In fact, the cosmological constant plays an important role in modern cosmology, although a very different one from what Einstein proposed. We will explore this in Section 25-7.)

Instead, the first hint that we live in an expanding universe came more than a decade later from the observations of Edwin Hubble. As we will see in Section 25-3, Hubble's discovery provides the resolution of Olbers's paradox.

CONCEPTCHECK 25-1

In an infinite, static universe uniformly filled with stars, would space be bright or dark when viewed from the Moon (looking away from the Sun)?

Answer appears at the end of the chapter.

25-2 The universe is expanding

TUTORIAL 25-1 Hubble is usually credited with discovering that our universe is expanding. He found a simple linear relationship between the distances to remote galaxies and the redshifts of the spectral lines of those galaxies (review Section 23-5, especially Figures 23-16 and 23-17). This relationship, now called the *Hubble law,* states that the greater the distance to a galaxy, the greater is the galaxy's redshift. Thus, remote galaxies are moving away from us with speeds proportional to their distances. Now let us see how Hubble's law reveals an expanding universe.

The Hubble Law and the Expanding Universe

The Hubble law can be stated as a very simple equation that relates the recessional velocity v of a galaxy to its distance d from Earth:

$$v = H_0 d$$

where H_0 is the Hubble constant. Because remote galaxies are getting farther and farther apart as time goes on, astronomers say that the universe is expanding. We say these galaxies are in the Hubble flow.

ANALOGY What does it actually mean to say that the universe is expanding? According to general relativity, space itself is not rigid. The amount of space between widely separated locations increases over time. A good analogy is that of baking a chocolate chip cake, as in Figure 25-2. As the cake expands during baking, the chocolate chips do not move through the cake but the amount of space between the chocolate chips gets larger and larger. In the same way, as the universe expands, galaxies in the Hubble flow do not move through space, but the amount of space between widely separated galaxies increases. The expansion of the universe *is* the expansion of space.

CAUTION! It is important to realize that the expansion of the universe occurs primarily in the vast spaces that separate clusters of galaxies. Just as the individual chocolate chips in Figure 25-2 do not expand as the cake expands during baking, galaxies themselves do not expand. Einstein and others have established that an object that is held together by its own gravity, such as a galaxy or a cluster of galaxies, creates a region of nonexpanding space. Likewise, molecular forces, which are much stronger than gravity, prevent expansion. For example, Earth and your body, which are held together by molecular forces, are not getting any bigger. Only the distance between widely separated galaxies increases with time. This expansion actually creates space. The *Cosmic Connections: "Urban Legends" about the Expanding Universe* has more to say about several misconceptions concerning the expanding universe.

The Hubble law is a direct proportionality—that is, a galaxy twice as far away is receding from us twice as fast. This property is just what we would expect in an expanding universe. To see why this property results from uniform expansion, imagine a grid of parallel lines (as on a piece of graph paper) crisscrossing the universe. Figure 25-3a shows a series of such gridlines 100 Mpc apart along with five galaxies labeled A, B, C, D, and E that happen to lie where gridlines cross. As the universe expands in all directions the gridlines and the attached galaxies spread apart. (This is just what would happen if the universe were a two-dimensional rubber sheet that was being pulled equally on all sides. Alternatively, you can imagine that Figure 25-3a depicts a very small portion of the chocolate chip cake in Figure 25-2, with galaxies taking the place of chocolate chips.)

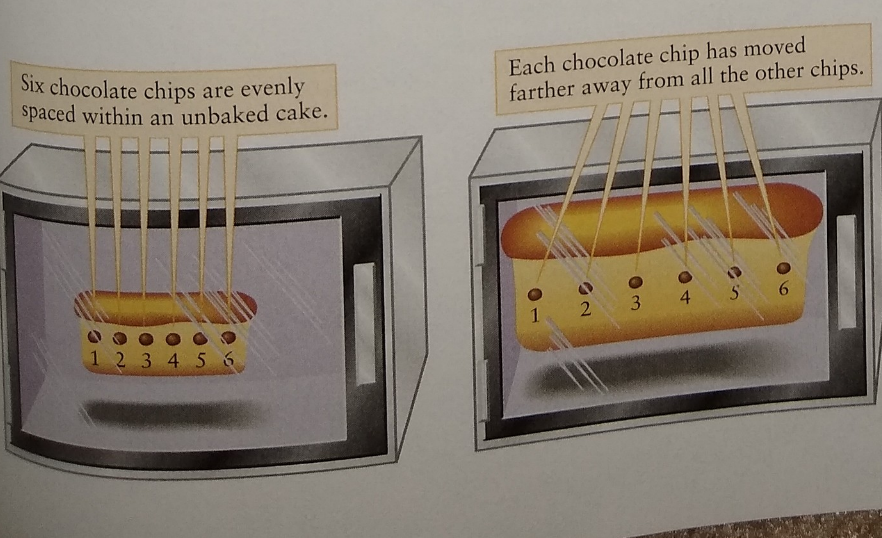
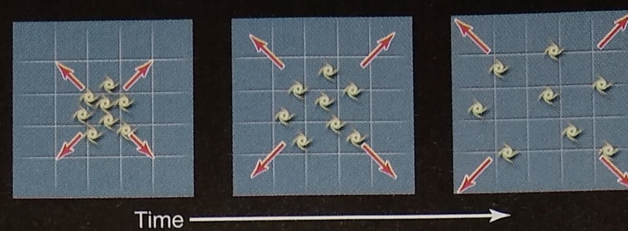


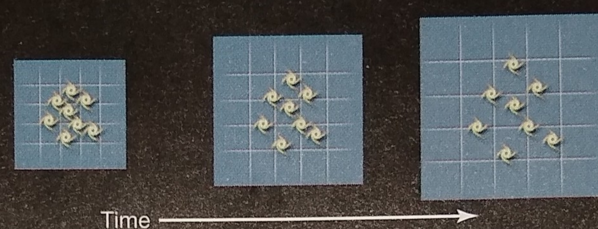
FIGURE 25-2
The Expanding Chocolate Chip Cake Analogy The expanding universe can be compared to what happens inside a chocolate chip cake as the cake expands during baking. All of the chocolate chips in the cake recede from one another as the cake expands, just as all the galaxies recede from one another as the universe expands.

"Urban Legends" about the Expanding Universe

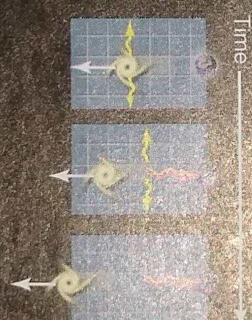
Incorrect Urban Legend #1:
The expansion of the universe means that as time goes by, galaxies move away from each other through empty space. In this picture, space is simply a background upon which the galaxies act out their parts .

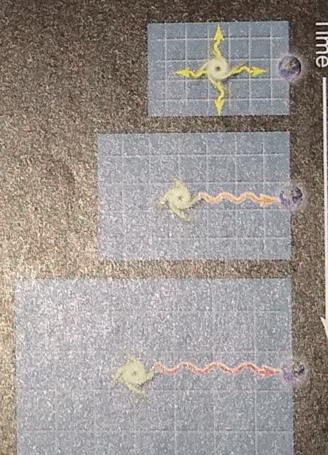


Reality:
The expansion of the universe means that as time goes by, space itself expands (shown here by the expanding grid). As it expands, it carries the galaxies along with it.



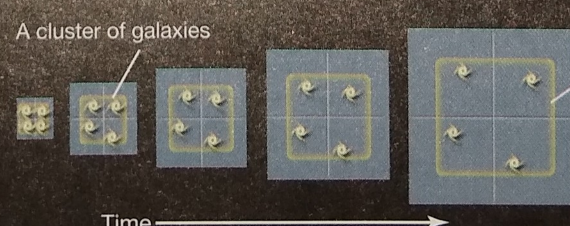
Incorrect Urban Legend #2:
The redshift of light from distant galaxies is a Doppler shift produced by galaxies moving away from us through an unchanging space. Once the light is emitted with its Doppler shift, the wavelength remains the same during its journey to us.





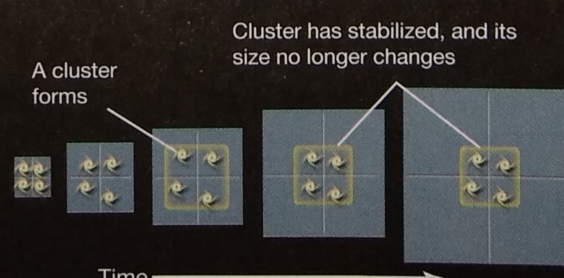
Reality:
As light travels through intergalactic space, its wavelength gradually expand as the
space through which it is travelling expands. This is called a cosmological redshif

Incorrect Urban Legend #3:
As the universe expands, so do objects within the universe. Hence galaxies within a cluster are now more spread out than they were billions of years ago.

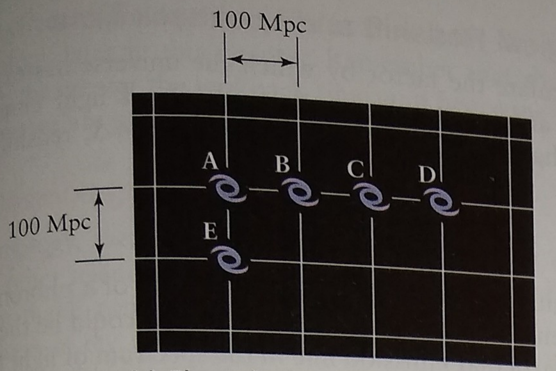


In this picture, the cluster expands as the universe expands.

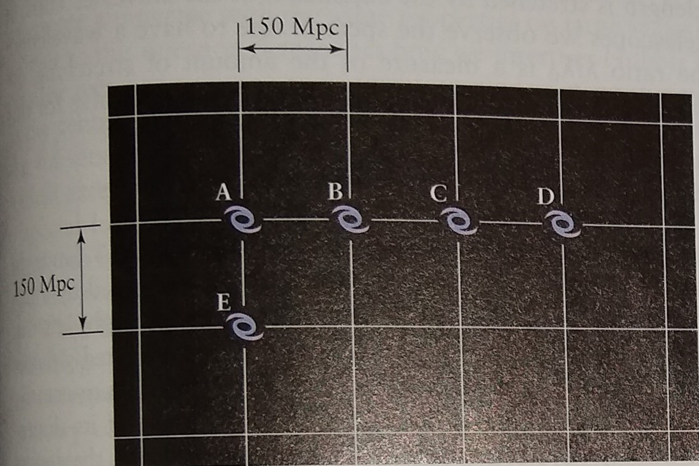
Reality:
At first the expansion of the universe tends to pull the galaxies of a cluster away from each other. But the force of gravitational attraction binds the members of the clusters together, so the cluster stabilizes at a certain size.



(Illustrations by Alfred T. Kamaj from C. H. Lineweaver and T. M Davis, "Misconceptions about Big Bang," *Scientific American* March 2005)



(a) Five galaxies spaced 100 Mpc apart



(b) The expansion of the universe spreads the galaxies apart

	Original distance (Mpc)	Later distance (Mpc)	Change in distance (Mpc)
A–B	100	150	50
A–C	200	300	100
A–D	300	450	150
A–E	100	150	50

ANIMATION 25-1

FIGURE 25-3

The Expanding Universe and the Hubble Law **(a)** Imagine five galaxies labeled A, B, C, D, and E. At the time shown here, adjacent galaxies are 100 Mpc apart. **(b)** As the universe expands, by some later time the spacing between adjacent galaxies has increased to 150 Mpc. The table shows that the greater the original distance between galaxies, the greater the amount that distance has increased. This agrees with the Hubble law.

Figure 25-3b shows the universe at a later time, when the gridlines are 50% farther apart (150 Mpc) and all the distances between galaxies are 50% greater than in Figure 25-3a. Imagine that A represents our Galaxy, the Milky Way. The table accompanying Figure 25-3 shows how far each of the other galaxies has moved away from us during the expansion: Galaxies A and B and galaxies A and E were originally 100 Mpc apart and have moved away from each other by an additional 50 Mpc; A and C, which were originally 200 Mpc apart, have increased their separation by an additional 100 Mpc; and the distance between A and D, originally 300 Mpc, has increased by an additional 150 Mpc. In other words, the increase in distance between any pair of galaxies is in direct proportion to the original distance; if the original distance is twice as great, the increase in distance is also twice as great.

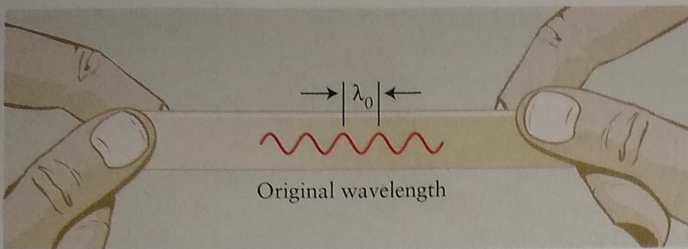
To see what these distances tell us about the recessional velocities of galaxies, remember that velocity is equal to the distance moved divided by the elapsed time. (For example, if you traveled in a straight line for 360 kilometers in 4 hours, your velocity was (360 km)/(4 h) = 90 kilometers per hour.) Because the distance that each galaxy moves away from A during the expansion is directly proportional to its original distance from A, it follows that the velocity v at which each galaxy moves away from A is also directly proportional to the original distance d. This result is just the Hubble law, $v = H_0 d$.

CAUTION! It may seem that if the universe is expanding, and if we see all the distant galaxies rushing away from us, then we must be in a special position at the very center of the universe. In fact, the expansion of the universe looks the same from the vantage point of *any* galaxy. For example, as seen from galaxy D in Figure 25-3, the initial distances to galaxies A, B, and C are 300 Mpc, 200 Mpc, and 100 Mpc, respectively. Between parts (a) and (b) of the figure, these distances increase by 150 Mpc, 100 Mpc, and 50 Mpc, respectively. So, as seen from D as well, the recessional velocity increases in direct proportion with the distance, and in the same proportion as seen from A. In other words, no matter which galaxy you call home, you will see all the other galaxies receding from you in accordance with the same Hubble law (and the same Hubble constant) that we observe from Earth.

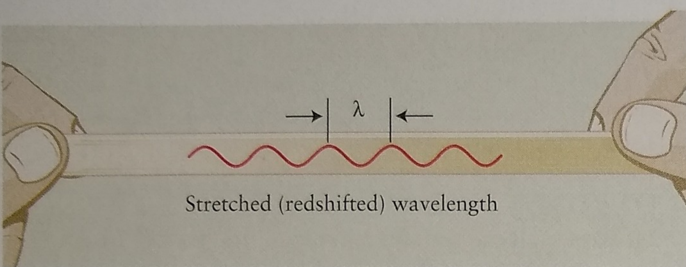
Figure 25-2 also shows that the expansion of the universe looks the same from one galaxy as from any other. An insect sitting on any one of the chocolate chips would see all the other chips moving away. If the cake were infinitely long, it would not actually have a center; as seen from any chocolate chip within such a cake, the cake would extend off to infinity to the left and to the right, and the expansion of the cake would appear to be centered on that chip. Likewise, because *every* point in the universe appears to be at the center of the expansion, it follows that our universe has no center at all.

CAUTION! "If the universe is expanding, what is it expanding into?" This commonly asked question arises only if we take our chocolate chip cake analogy too literally. In Figure 25-2, the cake (representing the universe) expands in three-dimensional space into the surrounding air. But the actual universe includes *all* space; there is no extra or additional space for the universe to expand into. Asking "What lies beyond the universe?" is like asking "Where on Earth is north of the North Pole?"—there just isn't a place on Earth that this point could be.

The ongoing expansion of space explains why the light from remote galaxies is redshifted. Imagine light or a photon coming toward us from a distant galaxy. As the photon travels through space, the space is expanding, so the photon's wavelength



(a) A wave drawn on a rubber band ...



(b) ... increases in wavelength as the rubber band is stretched.

FIGURE 25-4

Cosmological Redshift A wave drawn on a rubber band stretches along with the rubber band. In an analogous way, a light wave traveling through an expanding universe "stretches"; that is, its wavelength increases.

becomes stretched. When the photon reaches our eyes, we see an increased wavelength: The photon has been redshifted. The longer the photon's journey, the more its wavelength will have been stretched along the way. Thus, photons from distant galaxies have larger redshifts than those of photons from nearby galaxies, as expressed by the Hubble law.

The redshifts of distant galaxies are not Doppler shifts; they are caused by the expansion of space itself

A redshift caused by the expansion of the universe is properly called a **cosmological redshift.** It is *not* the same as a Doppler shift. Doppler shifts are caused by an object's *motion through space,* whereas a cosmological redshift is caused by the *expansion of space* (Figure 25-4).

In Hubble's law, the original interpretation of redshifts was that they were due to Doppler shifts by receding galaxies, and this works because for small redshifts, the Doppler shift can account for the recession of galaxies in expanding space. However, the full properties of expanding space, described by Einstein's general theory of relativity, must be taken into account for larger redshifts. In fact, at redshifts (z) greater than about $z > 1.5$, galaxies are observed with recessional velocities greater than the speed of light. While this would violate the laws of physics in a static universe, recessional speeds can exceed the speed of light in an expanding universe.

CONCEPTCHECK 25-2

Although nearly all distant galaxies have measureable redshifts, the relatively nearby Andromeda Galaxy exhibits an overall blue shift. What does this mean about the Andromeda Galaxy's movement?

Answer appears at the end of the chapter.

Cosmological Redshift and Lookback Time

We can calculate the factor by which the universe has expan since some ancient time from the redshift of light emitted objects at that time. As we saw in Section 24-5, redshift (z defined as

$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

In this equation λ_0 is the unshifted wavelength of a photon an is the wavelength we observe. For example, λ_0 could be the wa length of a particular emission line in the spectrum of light leav a remote galaxy. As the galaxy's light travels through space, wavelength is stretched by the expansion of the universe. Thus our telescopes we observe the spectral line to have a wavelen λ. The ratio λ/λ_0 is a measure of the amount of stretching. rearranging terms in the preceding equation, we can solve for ratio to obtain

$$\frac{\lambda}{\lambda_0} = 1 + z$$

For example, consider a galaxy with a redshift $z = 3$. Since time that light left that galaxy, the universe has expanded by a f tor of $1 + z = 1 + 3 = 4$. In other words, when the light left t galaxy, representative distances between widely separated gala were only one-quarter as large as they are today. A representat volume of space, which is proportional to the cube of its dim sions, was only $(1/4)^3 = 1/64$ as large as it is today. Thus, the dens of matter in such a volume was 64 times greater than it is today

If you know the redshift z of a distant object such as a rem galaxy, you can calculate that object's recessional velocity v (Box 23-2 for this calculation). Then, using the Hubble law, you c determine the distance d to that object if you know the value of Hubble constant H_0. This distance also tells you the **lookback ti** of that object, that is, how far into the past you are looking wh you see that object. For example, if the lookback time for a dista galaxy is a billion years, that means the light from the galaxy too billion years to reach us, so we are seeing it as it was a billion ye ago. The images that open this chapter show supernovae in dista galaxies with lookback times from 7.7 to 9.0 billion years.

Distances and lookback times determined in this way somewhat uncertain, because there is some uncertainty in t value of the Hubble constant. Furthermore, as we will see Section 25-8, the universe has not always expanded at the sa rate. This variable rate of expansion means that the value of t Hubble constant H_0 was different in the distant past. (In oth words, the Hubble "constant" is not actually constant in time, b at a given time it is still constant throughout space.) Furthermo the correct distance d to use in the Hubble law is not the distan at which we *see* the object, but rather the distance between us a the object *now.* This latter distance is larger because during t time that it takes light to reach us from a distant object, that obje has moved farther away due to the expansion of the universe.

To avoid dealing with these uncertainties and complicatio astronomers commonly refer to times in the distant past in terr of redshift rather than years. For example, instead of askin "How common were quasars 5 billion years ago?," an astronom might ask, "How common were quasars at $z = 1.0$?" In this que tion, "at $z = 1.0$" is a shorthand way of saying "at the lookba time that corresponds to objects at $z = 1.0$." We will use this terminology later in this chapter. Remember that the greater the redshift, the greater the lookback time, and hence the further back into time we are peering.

The Cosmological Principle

In cosmology, there is only one universe that we can observe. Unlike other sciences, we cannot carry out controlled experiments or even make comparisons between two similar systems, when the system is the universe itself. But then a question arises: Are we observing the universe from a special location, resulting in a unique, nonrepresentative appearance? Or would observers anywhere see a universe with the same properties on large scales? The answer to this question determines how we interpret Hubble's law, because receding galaxies could be interpreted to mean that we are at the center of the universe. The idea that we are at the center of the universe was rejected, however, because it violates a cosmological extension of Copernicus's argument that we do not occupy a special location in space. An expanding universe, on the other hand, has no center; at all locations in space, observers would see galaxies recede according to Hubble's law.

When Einstein began applying his general theory of relativity to cosmology, he made a daring assumption: Over very large distances the universe is **homogeneous**, meaning that every region is the same as every other region, and **isotropic**, meaning that the universe looks the same in every direction. In other words, if you could stand back and look at a very large region of space, any one part of the universe would look basically the same as any other part, with the same kinds of galaxies distributed through space in the same way. The assumption that the universe is homogeneous and isotropic constitutes the **cosmological principle**. It gives precise meaning to the idea that we do not occupy a special location in space.

Models of the universe based on the cosmological principle have proven remarkably successful in describing the structure and evolution of the universe and in interpreting observational data. More recently, direct observations reveal a homogeneous and isotropic universe on the largest scales—a validation of the cosmological principle. A homogenous and isotropic universe is revealed in maps made of large-scale structure, as shown in Figures 23-23 and 23-24. As we will see in Section 25-5, radiation left over from the Big Bang produces a similar result for the early universe.

CONCEPTCHECK 25-3

If we notice in the night sky that there are more stars along the Milky Way than in other regions of the sky, is this consistent or inconsistent with the cosmological principle?

CALCULATIONCHECK 25-1

What is the redshift z-value for a galaxy that has a galaxy spectral line shifted to 725.6 nm when a stationary object would emit the line at from 656.3 nm?

CALCULATIONCHECK 25-2

What is the distance to a galaxy that is observed to have a recessional velocity of 10,000 km/s?

Answers appear at the end of the chapter.

25-3 The expanding universe emerged from a cataclysmic event called the Big Bang

The Hubble flow shows that the universe has been expanding for billions of years. Therefore, we can conclude that in the past the matter in the universe must have been closer together and therefore denser than it is today. Indeed, as we look farther into the past, we clearly see the density of the universe increasing. There is even strong evidence of increasing density back to the first moments of time. Therefore, some sort of tremendous event caused high-density matter to begin the expansion that continues to the present day. This event, called the **Big Bang**, marks the creation of the universe.

CAUTION! It is not correct to think of the Big Bang as an explosion. When a bomb explodes, pieces of debris fly off *into space* from a central location. If you could trace all the pieces back to their origin, you could find out exactly where the bomb had been. This process is not possible with the universe, however, because the universe itself always has and always will consist of all space, with no center. There is no single or central location in space where the Big Bang occurred, because the Big Bang is the expansion of all space (see the discussion of the expanding chocolate chip cake in Section 25-2).

Estimating the Age of the Universe

How long ago did the Big Bang take place? To estimate an answer, imagine two galaxies that today are separated by a distance d and receding from each other with a velocity v. A movie of these galaxies would show them flying apart. If you run the movie backward, you would see the two galaxies approaching each other as time runs in reverse. We can calculate the time T_0 it will take for the reverse-run galaxies to collide by using the equation

$$T_0 = \frac{d}{v}$$

This expression says that the time to travel a distance d at velocity v is equal to the ratio d/v. (As an example, to travel a distance of 360 km at a velocity of 90 km/h takes (360 km)/(90 km/h) = 4 hours.) If we use the Hubble law, $v = H_0 d$, to replace the velocity v in this equation, we get

$$T_0 = \frac{d}{H_0 d} = \frac{1}{H_0}$$

Note that the distance of separation, d, has canceled out and does not appear in the final expression. Distance not appearing in the expression means that T_0 is the same for *all* galaxies. This period is the time in the past when all the matter in galaxies was crushed together, the time back to the Big Bang. In other words, the reciprocal (or inverse) of the Hubble constant H_0 gives us an estimate of the age of the universe called the **Hubble time**; this is one reason why H_0 is such an important quantity in cosmology.

Observations suggest that $H_0 = 73$ km/s/Mpc to within a few percent, and this is the value we choose as our standard (see Section 23-5). Using this value, our estimate for the age of the universe is

$$T_0 = \frac{1}{73 \text{ km/s/Mpc}}$$

To convert this into units of time, we simply need to remember that 1 Mpc equals 3.09×10^{19} km and 1 year equals 3.156×10^7 s. Using the technique we discussed in Box 1-3 for converting units, we get

$$T_0 = \frac{1}{73}\ \frac{\text{Mpc s}}{\text{km}} \times \frac{3.09 \times 10^{19}\ \text{km}}{1\ \text{Mpc}} \times \frac{1\ \text{year}}{3.156 \times 10^7 \text{s}}$$

$$= 1.34 \times 10^{10}\ \text{years} = 13.4\ \text{billion years}$$

By comparison, the age of our solar system is only 4.56 billion years, or about one-third the age of the universe. Thus, the formation of our home planet is a relatively recent event in the history of the cosmos.

The value of H_0 has an uncertainty of about 5%, so our simple estimate of the age of the universe is likewise uncertain by at least 5%. Furthermore, the formula $T_0 = 1/H_0$ is at best an approximation, because in deriving it we assumed that the universe expands at a constant rate. In Section 25-8 we will discuss how the expansion rate of the universe has changed over its history. When these factors are taken into consideration, we find that the age of the universe is 13.7 billion years, with an uncertainty of about 0.2 billion years. This time period is remarkably close to our simple estimate.

Whatever the true age of the universe, it must be at least as old as the oldest stars. The oldest stars that we can observe readily lie in the Milky Way's globular clusters (see Section 19-4 and Section 22-1). The most recent observations, combined with calculations based on the theory of stellar evolution, indicate that these stars are about 13.4 billion years old (time period with an uncertainty of about 6%). This time period is less than the calculated age of the universe: As required, the oldest stars in our universe are younger than the universe itself.

What was our universe like 15 billion years ago? The passage of time (as we understand time) in the only universe we know of did not exist prior to the Big Bang. Nor did space (as we understand space) exist in the universe until expansion from the Big Bang. Time began to pass and space began to exist at the Big Bang. Since the universe, as we understand it, is only 13.7 billion years old, there does not appear to be physical meaning to the question of what things were like in the universe 15 billion years ago.

CONCEPTCHECK 25-4

If the Hubble constant were smaller than it actually is, would the universe be younger or older than 13.7 billion years?

Answer appears at the end of the chapter.

Our Observable Universe and the Dark Night Sky

The Big Bang helps resolve Olbers's paradox, which we discussed in Section 25-1. We know that the universe had a definite beginning, and thus its age is finite (as opposed to infinite). If the universe is 13.7 billion years old, then the most distant objects that we can see are those whose light has traveled 13.7 billion years to reach us. (Due to the expansion of the universe, these objects are now more than 13.7 billion light-years away.) As a result, we can only see objects that lie within an immense sphere centered on Earth (Figure 25-5). This is true even if the universe is infinite, with galaxies scattered throughout its limitless expanse.

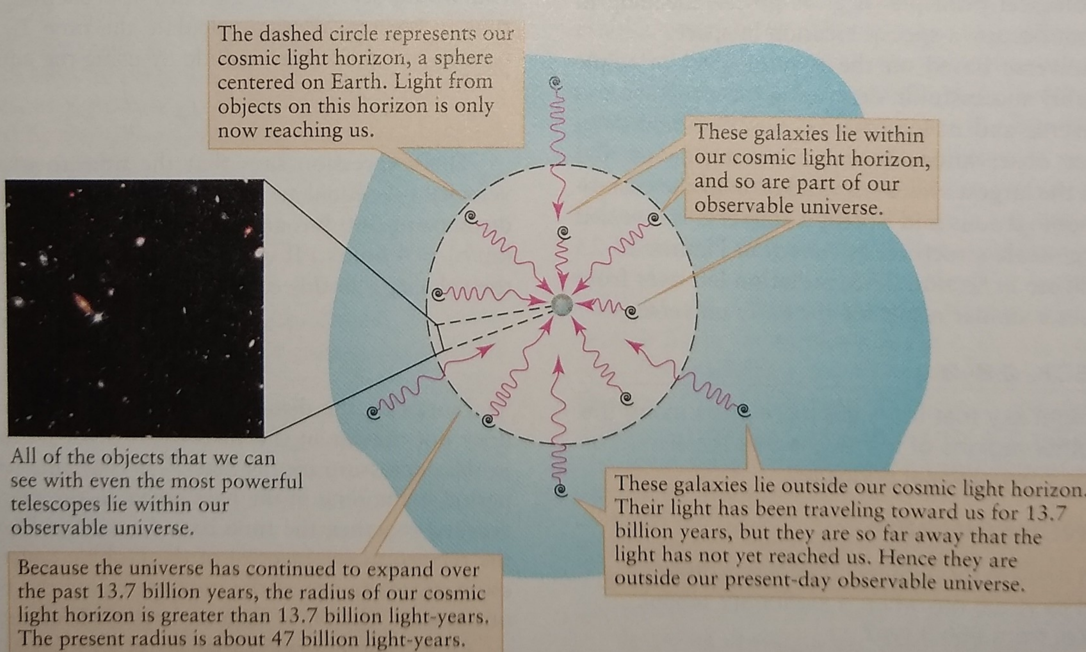


FIGURE 25-5 R I V U X G

Our Observable Universe The part of the universe that we can observe lies within our cosmic light horizon. The galaxies that we can just barely make out with our most powerful telescopes lie inside our cosmic light horizon; we see them as they were less than a billion years after the Big Bang. We cannot see objects beyond our cosmic light horizon, because in the 13.7 billion years since the Big Bang their light has not had enough time to reach us. (Inset: Robert Williams and the Hubble Deep Field Team, STScI; NASA)

The surface of the sphere depicted in Figure 25-5 is called our **cosmic light horizon.** Our entire **observable universe** is located inside this sphere. We cannot see anything beyond our cosmic light horizon, because the time required for light to reach us from these incredibly remote distances is greater than the present age of the universe. As time goes by, light from more distant parts of the universe reaches us for the first time, and the size of the cosmic light horizon—the size of our observable universe—increases. The finite size of the observable universe, with a finite number of stars and galaxies, also helps to resolve Olber's paradox: Galaxies are distributed sparsely enough in our observable universe that there are no stars along most of our lines of sight. This sparse distribution of visible stars is one reason why the night sky is dark.

Measuring the recessional velocities of galaxies allows us to estimate the age of the universe

Besides the finite age of the universe, a second effect also contributes significantly to the darkness of the night sky—the redshift. According to the Hubble law, the greater the distance to a galaxy, the greater the redshift. When a photon is redshifted, its wavelength becomes longer, and its energy—which is inversely proportional to its wavelength (see Section 5-5)—decreases. Consequently, even though there are many galaxies far from Earth, they have large redshifts and their light does not carry much energy. A galaxy nearly at the cosmic light horizon has a nearly infinite redshift, meaning that the light we receive from that galaxy carries practically no energy at all. This decrease in photon energy because of the expansion of the universe decreases the brilliance of remote galaxies, helping to make the night sky dark.

The concept of a Big Bang origin for the universe is a straightforward, logical consequence of an expanding universe. In Section 25-4, we will see direct evidence of the primordial fireball associated with the Big Bang and other confirmations of the Big Bang back to the first few moments. But how far back in time can our laws describe the universe? If you can just imagine far enough back into the past, you can arrive at a time 13.7 billion years ago, when the density throughout the universe was nearly infinite. As a result, throughout the universe space and time were jumbled up with nearly infinite curvature. A full description of this earliest instant requires (as do aspects of black holes) a valid mathematical theory of quantum gravity, which is a work in progress. But when in the past did the known laws of physics begin to apply?

A very short time after the Big Bang, space and time began to behave in the way we think of them today. This short time interval, called the **Planck time** (t_P), is given by the following expression:

The Planck time

$$t_P = \sqrt{\frac{Gh}{c^5}} = 1.35 \times 10^{-43}\ \text{s}$$

t_P = Planck time
G = universal constant of gravitation
h = Planck's constant
c = speed of light

We do not yet understand how space, time, and matter behaved in that brief but important interval from the beginning of the Big Bang to the Planck time, about 10^{-43} seconds later. (Indeed, the laws of physics suggest that it might be impossible ever to know what happened during this extremely short time interval.) Hence, the Planck time represents a limit to our knowledge of conditions at the very beginning of the universe.

CONCEPTCHECK 25-5

Consider two hypothetical stars of equal luminosity that are initially at the same remote distance from Earth, but each is in a different type of universe. Imagine one star in a static universe so that the star is not receding away. Imagine that the other star is receding away due to cosmic expansion, just as galaxies do in our actual universe. When this imaginary experiment begins and both stars are observed from Earth, which star, if any, appears dimmer?

CONCEPTCHECK 25-6

Why does our observable universe get larger over time?

Answer appears at the end of the chapter.

25-4 The microwave radiation that fills all space is evidence of a hot Big Bang

TUTORIAL 25-2

One of the major advances in twentieth-century astronomy was the discovery of the origin of the heavy elements. We know today that essentially all the heavy elements are created by thermonuclear reactions at the centers of stars and in supernovae (see Chapter 20). The starting point of all these reactions is the fusion of hydrogen into helium, which we described in Section 16-1. But as astronomers began to understand the details of thermonuclear synthesis in the 1960s, they were faced with a dilemma: There is far more helium in the universe than could have been created by hydrogen fusion in stars.

For example, the Sun consists of about 74% hydrogen and 25% helium by mass, and the universe as a whole is also about 25% helium. Some helium was produced by the thermonuclear fusion of hydrogen within stars, but calculations show that the amount of helium produced in this way is not nearly enough to account for the large fraction of helium observed in the universe. Because it was thought that the universe originally contained only hydrogen—the simplest of all the chemical elements—the presence of so much helium posed a major dilemma.

A Hot Big Bang and the Cosmic Microwave Background

Shortly after World War II, Ralph Alpher and Robert Hermann proposed that the universe immediately following the Big Bang must have been so incredibly hot that thermonuclear reactions occurred everywhere throughout space. Calculations for the amount of helium (and some other elements) produced by thermonuclear reactions in the first few minutes after the Big Bang are in extraordinary agreement with observations. This astounding prediction of the Big Bang was confirmed by detailed observations, which means that strong evidence for the Big Bang goes all the way back to the first few minutes of the universe.

Fortunately, predictions coming from the Big Bang theory did not stop there. Princeton University physicists Robert Dicke and P. J. E. Peebles calculated that in order for the entire universe to undergo the required thermonuclear reactions, in addition to charged particles, the early universe must have been very hot and filled with many high-energy, short-wavelength photons. With these photons interacting strongly with the "soup" of charged particles, the intensity distribution of photons formed blackbody radiation (see Figure 5-12).

The universe has expanded so much since those ancient times that all those short-wavelength photons have had their wavelengths stretched by a tremendous factor. As a result, they have become low-energy, long-wavelength photons. The temperature of this cosmic radiation field is now only a few degrees above absolute zero. By Wien's law, radiation at such a low temperature should have its peak intensity at microwave wavelengths of approximately 1 millimeter. Hence, this radiation field, which fills all of space, is called the **cosmic microwave background (CMB)**, or **cosmic background radiation.** In the early 1960s, Dicke and his colleagues began designing an antenna to detect this microwave radiation.

Meanwhile, just a few miles from Princeton University, Arno Penzias and Robert Wilson of Bell Telephone Laboratories in New Jersey were working on a new microwave horn antenna designed to relay telephone calls to Earth-orbiting communications satellites (Figure 25-6). Penzias and Wilson were deeply puzzled when, no matter where in the sky they pointed their antenna, they detected faint background noise. Thanks to a colleague, they learned about the work of Dicke and Peebles and realized that they had discovered the cooled-down cosmic background radiation left over from the hot Big Bang. Penzias and Wilson shared the 1978 Nobel Prize in Physics for their discovery.

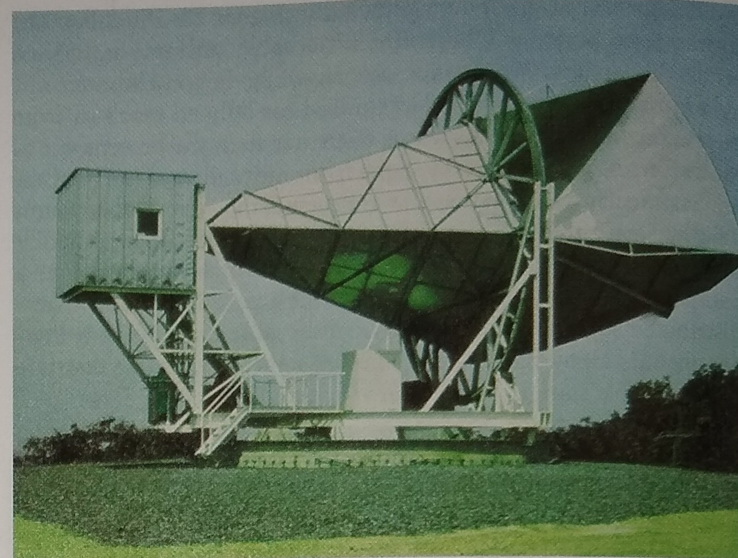


FIGURE 25-6 R I **V** U X G
The Bell Labs Horn Antenna Using this microwave horn antenna, originally built for communications purposes, Arno Penzias and Robert Wilson detected a signal that seemed to come from all parts of the sky. After carefully removing all potential sources of electronic "noise" (including bird droppings inside the antenna) that could create a false signal, Penzias and Wilson realized that they were actually detecting radiation from space. This radiation is the afterglow of the Big Bang. (Bell Labs)

The afterglow of the Big Bang was first discovered by a happy coincidence—and can be detected with an ordinary television

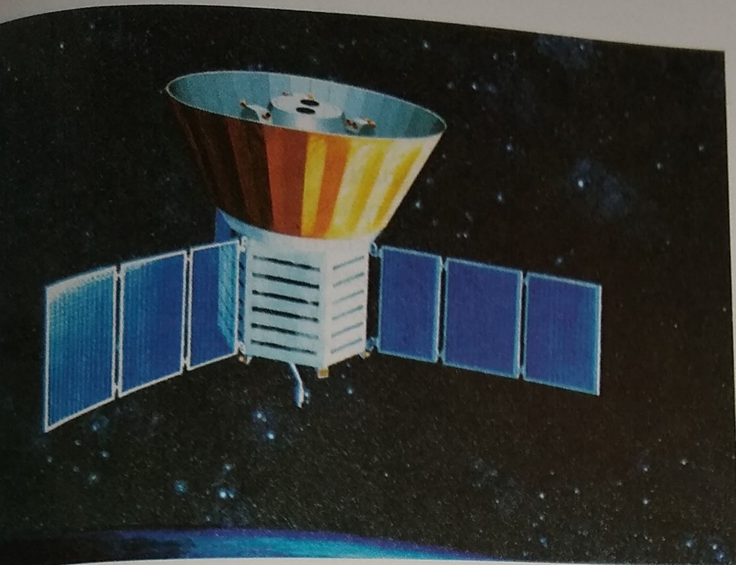
A TV using an antenna for signal reception (as opposed to cable or a satellite dish) can actually detect cosmic background radiation. This radiation is responsible for about 1% of the random noise or "hash" that appears on the screen when you tune a television to a station that is off the air. Using far more sophisticated detectors than TV sets, scientists have made many measurements of the intensity of the background radiation at a variety of wavelengths. Unfortunately, Earth's atmosphere is almost totally opaque to wavelengths between about 10 mm and 1 cm (see Figure 6-25), which is just the wavelength range in which the background radiation is most intense. As a result, scientists have had to place detectors either on high-altitude balloons (which can fly above the majority of the obscuring atmosphere) or, even better, on board orbiting spacecraft.

A Detailed Look at the Cosmic Microwave Background

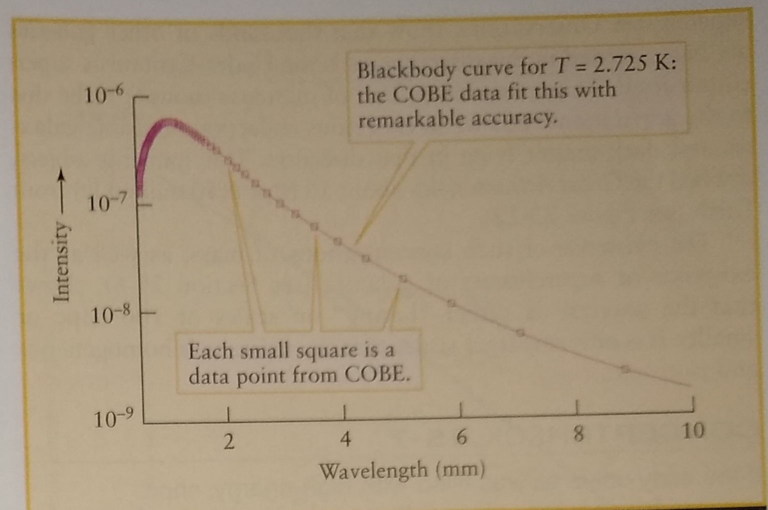
The first high-precision measurements of the cosmic microwave background came from the *Cosmic Background Explorer* (COBE, pronounced "coe-bee") satellite, which was placed in Earth orbit in 1989 (Figure 25-7a). Data from COBE's spectrometer, shown in Figure 25-7b, demonstrate that this ancient radiation has the spectrum of a blackbody with a temperature of 2.725 K. In recognition of this discovery, as well as others that we will discuss in Section 25-5, COBE team leaders John Mather of NASA and George Smoot of the University of California, Berkeley, were awarded the 2006 Nobel Prize in Physics.

An important feature of the microwave background is that its intensity is almost perfectly isotropic, that is, the same in all directions. In other words, we detect nearly the same background intensity from all parts of the sky. This is a striking confirmation of Einstein's assumption that the universe is isotropic (see Section 25-2). However, extremely accurate measurements, first made from high-flying airplanes and later from high-altitude balloons and from COBE, reveal a very slight variation in temperature across the sky. The microwave background appears slightly warmer than average toward the constellation of Leo and slightly cooler than average in the opposite direction toward Aquarius. Between the warm spot in Leo and the cool spot in Aquarius, the background temperature declines smoothly across the sky. Figure 25-8 is a map of the microwave sky showing this variation.

This apparent variation in temperature is caused by Earth's motion through the cosmos. If we were at rest with respect to the microwave background, the radiation would be even more nearly isotropic. Because we are moving through this radiation field, however, we see a Doppler shift. Specifically, we see shorter-than-average wavelengths in the direction toward which we are moving, as drawn in Figure 25-9. A decrease in wavelength corresponds to an increase in photon energy and thus an increase in the temperature of the radiation. The slight temperature excess observed, about 0.00337 K, corresponds to a speed of 371 km/s. Conversely, we see longer-than-average wavelengths in that part



(a) The COBE spacecraft



(b) The spectrum of the cosmic microwave background

FIGURE 25-7
COBE and the Spectrum of the Cosmic Microwave Background (a) The *Cosmic Background Explorer* (COBE), launched in 1989, measured the spectrum and angular distribution of the cosmic microwave background over a wavelength range from 1 mm to 1 cm. (b) A blackbody curve gives an excellent match to the COBE data. (a: Courtesy of J. Mather/NASA; b: Courtesy of E. Cheng/NASA COBE Science Team)

of the sky from which we are receding. An increase in wavelength corresponds to a decline in photon energy and, hence, a decline in radiation temperature.

Our solar system is thus traveling away from Aquarius and toward Leo at a speed of 371 km/s. Taking into account the known velocity of the Sun around the center of our Galaxy, we find that the entire Local Group of galaxies, including our Milky Way Galaxy, is moving at about 620 km/s toward the Hydra-Centaurus

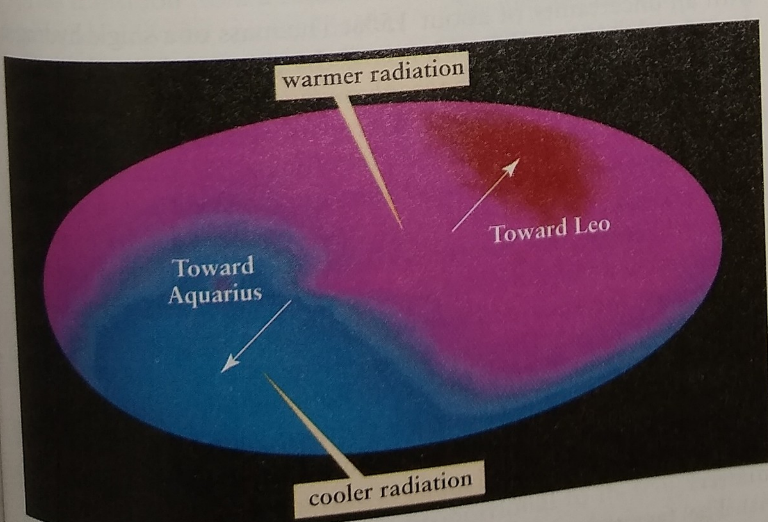


FIGURE 25-8 R I V U X G
The Microwave Sky In this map of the entire sky made from COBE data, the plane of the Milky Way runs horizontally across the map, with the galactic center in the middle. Color indicates temperature—red is warm and blue is cool. The small temperature variation across the sky—only 0.0033 K above or below the average radiation temperature of 2.725 K—is caused by Earth's motion through the microwave background. (NASA)

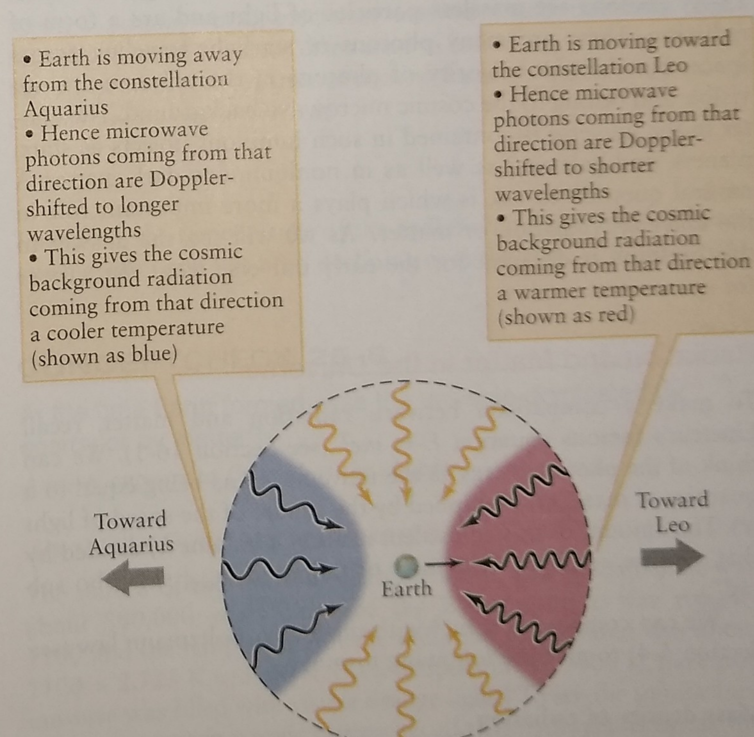


FIGURE 25-9
Our Motion Through the Microwave Background Because of the Doppler effect, we detect shorter wavelengths in the microwave background and a higher temperature of radiation in that part of the sky toward which we are moving. This part of the sky is the area shown in red in Figure 25-8. In the opposite part of the sky, shown in blue in Figure 25-8, the microwave radiation has longer wavelengths and a cooler temperature.

supercluster. Observations show that thousands of other galaxies are being carried in this direction, as is the Hydra-Centaurus supercluster itself. This tremendous flow of matter is thought to be due to the gravitational pull of an enormous collection of visible galaxies and dark matter lying in that direction. This immense object, dubbed the *Great Attractor*, lies about 50 Mpc (150 million ly) from Earth (see Figure 23-22).

The existence of such concentrations of mass, as well as the existence of superclusters of galaxies (see Section 21-6), shows that the universe is rather "lumpy" on scales of 100 Mpc or smaller. It is only on larger scales that the universe is homogeneous and isotropic.

CONCEPTCHECK 25-7

If the early universe was filled with high-energy, short-wavelength photons, why are these observed today to be low-energy, long-wavelength microwave photons?

Answer appears at the end of the chapter.

25-5 The universe was a hot, opaque plasma during its first 380,000 years

Energy in the universe falls into one of two categories—radiation or matter. (We will encounter another type of energy in Section 25-7.) Photons are massless particles of light and are a form of radiation. There are many photons of starlight traveling across space, but the vast majority of photons in the universe are not visible and belong to the cosmic microwave background. The matter in the universe is contained in such luminous objects as stars, planets, and galaxies, as well as in nonluminous dark matter. A natural question to ask is which plays a more important role in the universe: radiation or matter? As we will see, the answer to this question is different for the early universe from the answer for our universe today.

Radiation and Matter in the Universe

To make a comparison between radiation and matter, recall Einstein's famous equation $E = mc^2$ (see Section 16-1). We can think of the photon energy in the universe (E) as being equal to a quantity of mass (m) multiplied by the square of the speed of light (c). The amount of this equivalent mass in a volume V, divided by that volume, is the **mass density of radiation** (ρ_{rad}; say "rho sub rad").

We can combine $E = mc^2$ with the Stefan-Boltzmann law (see Section 5-4) to give the following formula:

Mass density of radiation

$$\rho_{rad} = \frac{4\sigma T^4}{c^3}$$

ρ_{rad} = mass density of radiation

T = temperature of radiation

σ = Stefan-Boltzmann constant = 5.67×10^{-8} W m^{-2} K^{-4}

c = speed of light = 3.00×10^8 m/s

For the present-day temperature of the cosmic backgrour radiation, $T = 2.725$ K, this equation yields

$$\rho_{rad} = 4.6 \times 10^{-31} \text{ kg/m}^3$$

The **average density of matter** (ρ_m; say "rho sub em") in th universe is harder to determine. To find this density, we look a large volume (V) of space, determine the total mass (M) of a the stars, galaxies, and dark matter in that volume, and divide th volume into the mass: $\rho_m = M/V$. (We emphasize that this quanti is the *average* density of matter. It would be the actual density if a the matter in the universe were spread out uniformly rather tha being clumped into galaxies and clusters of galaxies.) Determinin how much mass is in a large volume of space is a challenging tas A major part of the challenge involves dark matter, which emits n electromagnetic radiation and can be detected only by its gravita tional influence (see Section 22-4 and Section 23-8).

One method that appears to deal successfully with this cha lenge is to observe clusters of galaxies, within which most of th luminous mass in the universe is concentrated and the contribu tion from dark matter can also be estimated. Rich clusters ar surrounded by halos of hot, X-ray–emitting gas, typically at tem peratures of 10^7 to 10^8 K (see Figure 23-26). Such a halo shoul be in hydrostatic equilibrium, so that it neither expands no contracts but remains the same size (see Section 16-2, especiall Figure 16-2). The outward gas pressure associated with the halo' high temperature would then be balanced by the inward gravita tional pull due to the total mass of the cluster. Thus, by measurin the temperature of the halo—which can be determined from th properties of the halo's X-ray emission—astronomers can infer th cluster's mass, including the contribution from dark matter!

From galaxy clusters and other measurements, the present-day average density of matter in the universe is estimated to be

$$\rho_m = 2.4 \times 10^{-27} \text{ kg/m}^3$$

with an uncertainty of about 15%. The mass of a single hydrogen atom is 1.67×10^{-27} kg. Hence, if the mass of the universe were spread uniformly over space, there would be the equivalent of 1½ hydrogen atoms per cubic meter of space. By contrast, there are 5×10^{25} atoms in a cubic meter of the air you breathe! The very small value of ρ_m shows that our universe has a very low average density.

Furthermore, by counting galaxies and other measurements, astronomers determine that the average density of *luminous* matter (that is, the stars and gas within clusters of galaxies) is about 4.2×10^{-28} kg/m^3. This density is only about 17% of the average density of matter of all forms. Thus, nonluminous dark matter is actually the predominant form of matter in our universe. The "ordinary" matter (protons and neutrons) of which the stars, the planets, and ourselves are made is only about one-fifth of the total matter!

The fact that there is more dark matter than regular matter does not make it any easier to detect. By interacting with light, regular matter can cool and condense into stars and planets. However, dark matter is more evenly and sparsely distributed. The actual amount of dark matter within Earth's volume at any given time is only about 1 kg. It is thought that dark matter particles stream right through the Earth with only rare interactions. Due to its elusive nature, yet dominance over regular matter, the detection of dark matter particles is considered one of the "Holy Grails" of physics and astronomy and would surely result in a Nobel Prize.

When Radiation Held Sway Over Matter

Although the average density of matter in the universe is tiny by Earth standards, it is thousands of times larger than ρ_{rad}, the mass density of radiation. However, this ratio was not always the case. Matter prevails over radiation today only because the energy now carried by microwave photons is so small. Nevertheless, the number of photons in the microwave background is astounding. From the physics of blackbody radiation it can be calculated that there are today 410 million (4.1×10^8) photons in every cubic meter of space. In other words, the photons in space outnumber atoms by roughly a billion (10^9) to one. In terms of total number of particles, the universe thus consists almost entirely of microwave photons. This radiation field no longer has much effect on the universe however, because its photons have been redshifted to long wavelengths and low energies after 13.7 billion years of being stretched by the expansion of the universe.

In contrast, think back toward the Big Bang. The universe becomes increasingly compressed, and thus the density of matter increases as we go back in time. The photons in the background radiation also become more crowded together as we go back in time. But, in addition, the photons become less redshifted and thus have shorter wavelengths and higher energy than they do today. Because of this added energy, the mass density of radiation (ρ_{rad}) increases more quickly as we go back in time than does the average density of matter (ρ_m). In fact, as Figure 25-10 shows, there was a time in the ancient past when ρ_{rad} equaled ρ_m. Before this time, ρ_{rad} was greater than ρ_m, and radiation thus held sway over matter. Astronomers call this state a **radiation-dominated universe.** After ρ_m became greater than ρ_{rad}, so that matter prevailed over radiation, our universe became a **matter-dominated universe.**

This transition from a radiation-dominated universe to a matter-dominated universe occurred about 24,000 years after the Big Bang, at a time that corresponds to a redshift of about $z = 5200$. Since that time the wavelengths of photons have been stretched by a factor of $1 + z$, or about 5200. Today these microwave photons typically have wavelengths of about 1 mm. But when the universe was about 24,000 years old, they had wavelengths of about 190 nm in the ultraviolet part of the spectrum.

> The temperature of the background radiation has declined over the eons thanks to the expansion of the universe

To calculate the temperature of the cosmic background radiation at the time of this transition from a radiation-dominated universe to a matter-dominated one, we use Wien's law (see Section 5-4). This law says that the wavelength of maximum emission (λ_{max}) of a blackbody is inversely proportional to its temperature (T): A *decrease* of λ_{max} by a factor of 2 corresponds to an *increase* of T by a factor of 2.

The present-day peak wavelength of the cosmic background radiation corresponds to a blackbody temperature of 2.725 K. Hence, a peak wavelength 5200 times smaller corresponds to a temperature 5200 times greater: $T = 5200 \times 2.725\ \text{K} = 14{,}000\ \text{K}$. In other words, the radiation temperature at redshift z was greater than the present-day radiation temperature by a factor of $1 + z$.

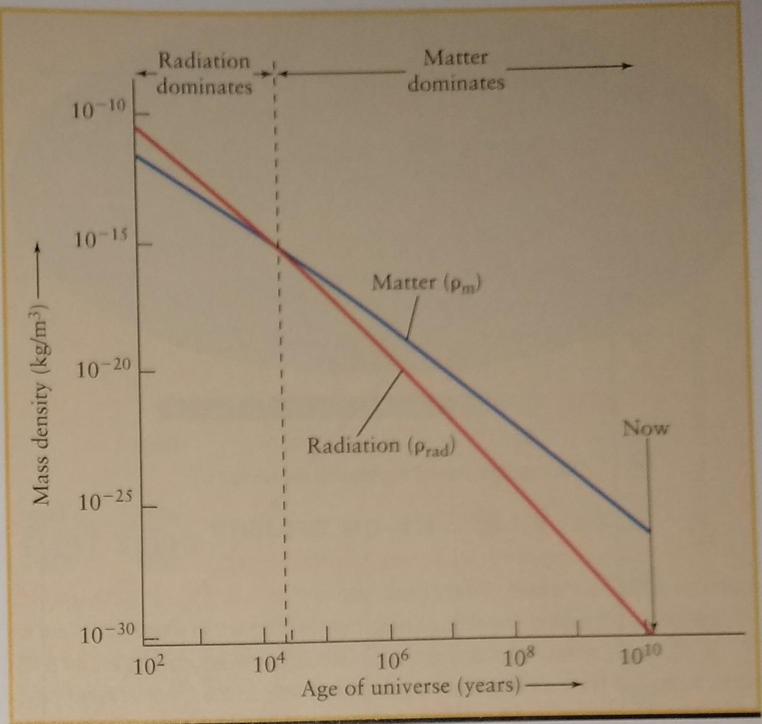


FIGURE 25-10
The Evolution of Density For approximately 24,000 years after the Big Bang, the mass density of radiation (ρ_{rad}, shown in red) exceeded the matter density (ρ_m, shown in blue), and the universe was radiation-dominated. Later, however, continued expansion of the universe caused ρ_{rad} to become less than ρ_m, at which point the universe became matter-dominated. (Graph courtesy of Clem Pryke, University of Minnesota)

Therefore, the temperature of the radiation background was once much greater and has been declining over the ages, as Figure 25-11 shows.

CONCEPTCHECK 25-8

At the time Earth formed, was the universe dominated by energy or by matter?

Answer appears at the end of the chapter.

When the First Atoms Formed

The nature of the universe changed again in a fundamental way about 380,000 years after the Big Bang, when z was roughly 1100 and the temperature of the radiation background was about $1100 \times 2.725\ \text{K} = 3000\ \text{K}$. (At a temperature of 3000 K, the entire universe was filled with visible orange light.) To see the significance of this moment in cosmic history, recall that hydrogen is by far the most abundant element in the universe—hydrogen atoms outnumber helium atoms by about 12 to 1. A hydrogen atom consists of a single proton orbited by a single electron, and it takes relatively little energy to knock the electron completely out of its orbit around the proton. In fact, ultraviolet radiation warmer than about 3000 K easily ionizes hydrogen. Thus, neutral hydrogen atoms could not survive in the universe that existed before $z = 1100$. That is, in the first 380,000 years after the Big Bang, the background photons

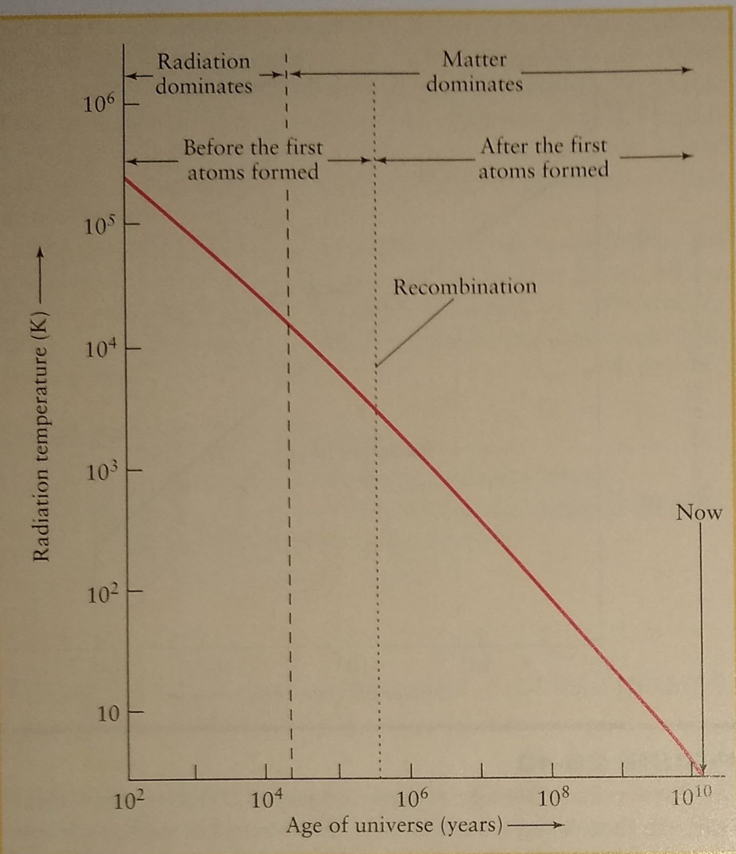


FIGURE 25-11

The Evolution of Radiation Temperature As the universe expanded, the photons in the radiation background became increasingly redshifted and the temperature of the radiation fell. Approximately 380,000 years after the Big Bang, when the temperature fell below 3000 K, hydrogen atoms formed and the radiation field "decoupled" from the matter in the universe. After that point, the temperature of matter in the universe was not the same as the temperature of radiation. The time when the first atoms formed is called the era of recombination (see Figure 25-12). (Graph courtesy of Clem Pryke, University of Minnesota)

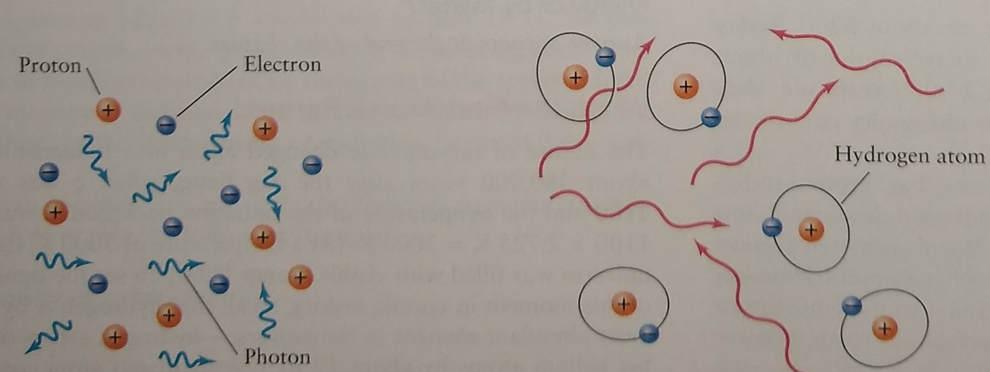
had energies great enough to prevent electrons and protons from binding to form hydrogen atoms (Figure 25-12a). Only since $z = 1100$ (that is, since $t = 380{,}000$ years) have the energies of these photons been low enough to permit hydrogen atoms to exist (Figure 25-12b).

The epoch when atoms first formed at $t = 380{,}000$ years is called the **era of recombination.** This name refers to electrons "recombining" to form atoms. (The name is a bit misleading, because the electrons and protons had never before combined into atoms.)

Prior to $t = 380{,}000$ years, the universe was completely filled with a shimmering expanse of high-energy photons colliding vigorously with protons and electrons. This state of matter, called a **plasma,** is opaque, which means that light cannot pass through it without being strongly scattered and absorbed. The surface and interior of the Sun are also a hot, glowing, opaque plasma (see Section 16-9). P. J. E. Peebles coined the term **primordial fireball** to describe the universe during its first 380,000 years of existence.

After $t = 380{,}000$ years, the photons no longer had enough energy to keep the protons and electrons apart. As soon as the temperature of the radiation field fell below about 3000 K, protons and electrons began combining to form hydrogen atoms. These atoms do not absorb low-energy photons, so space became transparent! All the photons that heretofore had been vigorously colliding with charged particles could now stream unimpeded across space. Today, these same photons constitute the microwave background.

The significance of the era of recombination becomes clear by considering how it affects an astronomer's ability to form images of the early universe. After recombination, the photons from a large clump of matter can stream to us while having very little interaction with the matter they pass through along their journey. These undisturbed photons can carry images of different clumps of matter in the early universe. On the other hand, photons emitted prior to recombination are scattered so strongly that any image from that early time is completely blurred out before its photons reach us. Therefore, *the era of recombination marks the*



(a) Before recombination:
- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque: Photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.

(b) After recombination:
- Temperatures became low enough for hydrogen atoms to form.
- The universe became transparent: Collisions between photons and atoms became infrequent.
- Matter and radiation were no longer at the same temperature.

FIGURE 25-12

The Era of Recombination (a) Before recombination, the energy of photons in the cosmic background was high enough to prevent protons and electrons from forming hydrogen atoms. (b) Some 380,000 years after the Big Bang, the energy of the cosmic background radiation became low enough that hydrogen atoms could survive.

earliest time and farthest distance that astronomers can collect images of the universe.

Before recombination, matter and the radiation field had the same temperature, because photons, electrons, and protons were all in continuous interaction with one another. After recombination, photons and atoms hardly interacted at all, and thus the temperature of matter in the universe was no longer the same as the temperature of the background radiation. Thus, $T = 2.725$ K is the temperature of the present-day background radiation field, *not* the temperature of the matter in the universe. Note that while the temperature of the background radiation is very uniform, the temperature of matter in the universe is anything but: It ranges from hundreds of millions of kelvins in the interiors of giant stars to a few tens of kelvins in the interstellar medium.

ANALOGY A good analogy is the behavior of a glass of cold water. If you hold the glass in your hand, the water will get warmer and your hand will get colder until both the water and your hand are at the same temperature. But if you set the glass down and do not touch it, so that the glass and your hand do not interact, their temperatures are decoupled: The water will stay cold and your hand will stay warm for much longer.

Because the universe was opaque prior to $t = 380{,}000$ years, we cannot see any further into the past than the era of recombination. In particular, we cannot see back to the era when the universe was radiation-dominated. The microwave background, whose photons have suffered a redshift of $z = 1100$, contains the most ancient photons we will ever be able to observe.

CONCEPTCHECK 25-9

If the universe had cooled more slowly, would the first atoms have appeared more quickly or more slowly?

Answer appears at the end of the chapter.

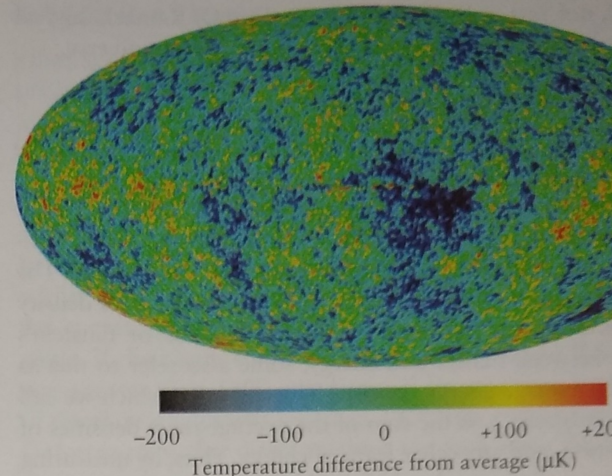
Nonuniformities in the Early Universe and the Origin of Galaxies

The COBE data show that the universe is full of blackbody radiation with a temperature of 2.725 K. (This is the cosmic microwave background radiation, or CMB, discussed in Section 25-4.) However, more sensitive observations show that there are slight temperature variations spread across the sky (Figure 25-13). What do these temperature variations tell us?

The distribution of matter in the early universe was not perfectly uniform, and these temperature variations reveal the nonuniformities—the clumps and voids—in the mass distribution. It is important to understand that the temperature fluctuations do not arise from the temperature of the matter. Instead, clumps in the distribution of matter produce a gravitational redshift (see Figure 21-7b) on the CMB photons as they leave a denser region. Redshifted CMB photons not only have longer wavelengths and lower energy, but also correspond to lower CMB temperatures. Thus, in Figure 25-13, the cooler bluer spots correspond to denser regions.

Astronomers place great importance on studying temperature and density variations in the cosmic background radiation. The reason is that clumps of matter seen at early times are the "seeds" of structures that continued to "grow" into today's superclusters of galaxies through gravitational contraction. Within these immense concentrations formed the galaxies, stars, and planets. Thus, by studying these nonuniformities, we are really studying the origins of our present-day structure.

Temperature variations in the cosmic background radiation do more than show us the origins of large-scale structure in the universe. As we will see in the next two sections, these temperature variations actually reveal the shape of the universe as a whole, and many of its most fundamental properties.



ANIMATION 25-2 ANIMATION 25-3 **FIGURE 25-13** R I V U X G **Temperature Variations in the Cosmic Microwave Background** This map from WMAP data shows small variations in the temperature of the cosmic background radiation across the entire sky. (The variations due to Earth's motions through space, shown in Figure 25-8, have been factored out.) Lower-temperature regions (shown in blue) show where the early universe was slightly denser than average; warmer regions (shown in red) correspond to regions where the density of matter was less dense than average. Note that the temperature variations in this figure are no more than 200 μK, or 2×10^{-4} K; these are tiny fluctuations around the blackbody radiation measured by COBE in Figure 25-7. (NASA/WMAP Science Team)

CONCEPTCHECK 25-10

Consider a blue patch in Figure 25-13. If astronomers looked at the same region with a visible-light telescope, what are they likely to see?

Answer appears at the end of the chapter.

25-6 The shape of the universe indicates its matter and energy content

We have seen that by following the mass densities of radiation (ρ_{rad}) and of matter (ρ_m), we can learn about the evolution of the universe. But it is equally important to know the combined mass density of *all* forms of matter and energy. (In an analogous way, an accountant needs to know the overall financial status of a company, not just individual profits or losses.) Remarkably, we can do this by investigating the overall shape of the universe.

The Curvature of the Universe

Einstein's general theory of relativity explains that gravity curves the fabric of space. Furthermore, the equivalence between matter and energy, expressed by Einstein's equation $E = mc^2$, tells that either matter or energy produces gravity. Thus, the matter and energy scattered across space should give the universe an overall curvature. The degree of curvature depends on the **combined average mass density** of all forms of matter and energy. (Again, because of Einstein's equivalence between matter and energy, some also refer to this as the combined average energy density.) This quantity, which we call ρ_0 (say "rho sub zero"), is the sum of the average mass densities of matter, radiation, and any other form of energy. Thus, by measuring the curvature of space, we should be able to determine the value of ρ_0 and, hence, learn about the content of the universe as a whole.

To see what astronomers mean by the curvature of the universe, imagine shining two powerful laser beams out into space so that they are perfectly parallel as they leave Earth. Furthermore, suppose that nothing gets in the way of these two beams, so we can follow them for billions of light-years as they travel across the universe and across the space whose curvature we wish to detect. Figure 25-14 illustrates the only three possibilities:

1. We might find that our two beams of light remain perfectly parallel, even after traversing billions of light-years. In this case, space would not be curved: The universe would have **zero curvature**, and space would be **flat**.

2. Alternatively, we might find that our two beams of light gradually converge. In such a case, space would not be flat. Recall that lines of longitude on Earth's surface are parallel at the equator but intersect at the poles. Thus, in this case the three-dimensional geometry of the universe would be analogous to the two-dimensional geometry of a spherical surface. We would then say that space is **spherical** and that the universe has **positive curvature.** Such a universe is also called **closed,** because if you travel in a straight line in any direction in such a universe, you will eventually return to your starting point.

3. Finally, we might find that the two initially parallel beams of light would gradually diverge, becoming farther and farther apart as they moved across the universe. In this case, the universe would still have to be curved, but in the opposite sense from the spherical model. We would then say that the universe has **negative curvature.** In the same way that a sphere is a positively curved two-dimensional surface, a saddle is a good example of a negatively curved two-dimensional surface. Parallel lines drawn on a sphere always converge, but parallel lines drawn on a saddle always diverge. Mathematicians say that saddle-shaped surfaces are hyperbolic. Thus, in a negatively curved universe, we would describe space as **hyperbolic.** Such a universe is also called **open** because if you were to travel in a straight line in any direction, you would never return to your starting point.

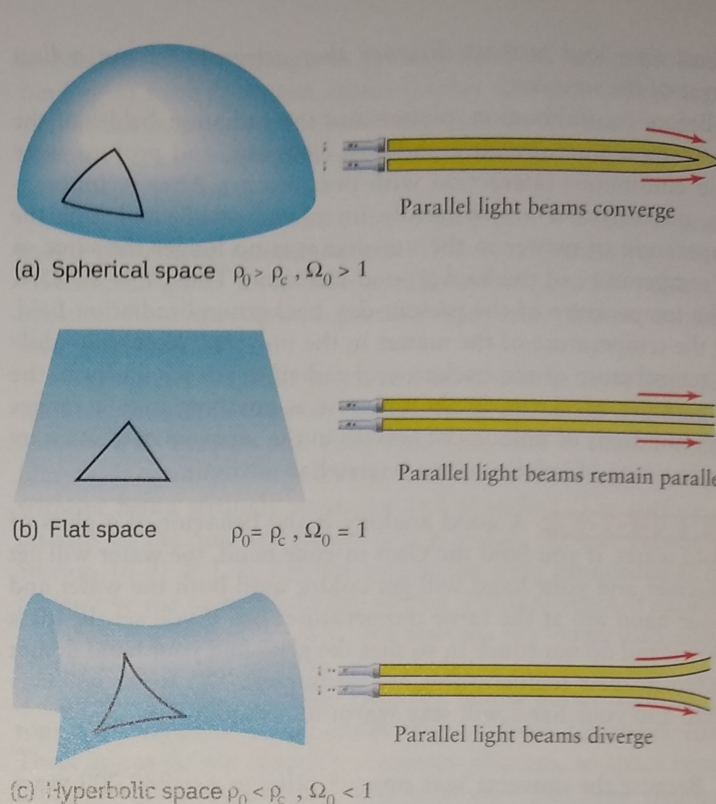


FIGURE 25-14

The Geometry of the Universe The curvature of the universe is either (a) positive, (b) zero, or (c) negative. The curvature depends on whether the combined mass density is greater than, equal to, or less than the critical density, or, equivalently, on whether the density parameter Ω_0 is greater than, equal to, or less than 1. In theory, the curvature could be determined by seeing whether two laser beams initially parallel to each other would converge, remain parallel, or spread apart.

Figure 25-14 summarizes the three cases of positive curvature, zero curvature, and negative curvature. Real space is three-dimensional, but we have drawn the three cases as analogous, more easily visualized two-dimensional surfaces. Therefore, as you examine the drawings in Figure 25-14, remember that the real universe has one more dimension. For example, if the universe is in fact hyperbolic, then the geometry of space must be the (difficult to visualize) three-dimensional analog of the two-dimensional surface of a saddle.

Note that in accordance with the cosmological principle, none of these models of the universe has an "edge" or a "center." This is clearly the case for both the flat and hyperbolic universes, because they are infinite and extend forever in all directions. A spherical universe is finite, but it also lacks a center and an edge. You could walk forever around the surface of a sphere (like the surface of Earth) without finding a center or an edge.

CONCEPTCHECK 25-11

If two lasers are aligned to be perfectly parallel out in a region of space far from any galaxies, could the geometry of space ever cause their light beams to cross?

Answer appears at the end of the chapter.

Density Determines Curvature

The curvature of the universe is determined by the actual value of the combined mass density ρ_0 and a reference density called the **critical density** ρ_c (say "rho sub cee"). If ρ_0 is greater than the critical density ρ_c, the universe has positive curvature and is closed. If ρ_0 is less than ρ_c, the universe has negative curvature and is open. In the special case that ρ_0 is exactly equal to ρ_c, the universe is flat. Clearly, the critical density plays a crucial role in determining the geometry of the universe. It is given by the expression

Critical density of the universe

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

ρ_c = critical density of the universe

H_0 = Hubble constant

G = universal constant of gravitation

Using a Hubble constant $H_0 = 73$ km/s/Mpc, we get

$$\rho_c = 1.0 \times 10^{-26} \text{ kg/m}^3$$

This critical density amounts to only about 5 hydrogen atoms per cubic meter! Even with the vast empty spaces between the stars, this density is about a million times less than the density of matter from stars and gas in the disk in our Milky Way Galaxy.

Many astronomers prefer to characterize the combined average mass density of the universe in terms of the **density parameter** Ω_0 (say "omega sub zero"). This parameter is just the ratio of the combined average mass density to the critical density:

Density parameter

$$\Omega_0 = \frac{\rho_0}{\rho_c}$$

Ω_0 = density parameter

ρ_0 = combined average mass density

ρ_c = critical density

An open universe (negative curvature) has a density parameter Ω_0 between 0 and 1, and a closed universe (positive curvature) has Ω_0 greater than 1. In a flat universe, Ω_0 is equal to 1. Thus, we can use the value of Ω_0 as a measure of the curvature of the universe (Table 25-1).

CALCULATIONCHECK 25-3

What is the combined average mass density (in kg/m³) in a fla universe?

Answer appears at the end of the chapter.

Measuring the Cosmic Curvature

How can we determine the curvature of space across the universe In theory, if you drew an enormous triangle whose sides were eac a billion light-years long (see Figure 25-14), you could determin the curvature of space by measuring the three angles of the tr angle. If their sum equaled 180°, space would be flat. If the sur was greater than 180°, space would be spherical. And if the sur of the three angles was less than 180°, space would be hyperbolic Unfortunately, this direct method for measuring the curvature c space is not practical.

A way to determine the curvature of the universe that is bot practical and precise is to see if light rays bend toward or awa from each other, as shown in Figure 25-14. The greater the dis tance a pair of light rays has traveled, and hence, the longer th time the light has been in flight, the more pronounced any sucl bending should be. Therefore, astronomers test for the presence o such bending by examining the oldest radiation in the universe— the cosmic microwave background.

If the cosmic microwave background were truly isotropic, sc that equal amounts of radiation reached us from all directions ir the sky, it would be impossible to tell whether individual light rays have been bent. However, as we saw in Section 25-5, there are localized "hot spots" in the cosmic microwave background due to density variations in the early universe. The apparent size of these hot spots depends on the curvature of the universe (Figure 25-15). If the universe is closed, the bending of light rays from a hot spot will make the spot appear larger (Figure 25-15a); if the universe is open, the light rays will bend the other way and the hot spots will appear smaller (Figure 25-15c). Only in a flat universe will the light rays travel along straight lines, so that the hot spots appear with their true size (Figure 25-15b).

By calculating what conditions were like in the primordial fireball, astrophysicists find that in a flat universe, the dominant "hot spots" in the cosmic background radiation should have an angular size of about 1°. (In Section 25-9 we will learn how this is deduced.) This is just what observations of the CMB have confirmed (see Figure 25-13). Hence, the curvature of the universe must be very close to zero, and the universe must be either flat or very nearly so.

TABLE 25-1 The Geometry and Average Density of the Universe

Geometry of space	Curvature of space	Type of universe	Combined average mass density (ρ_0)	Density parameter (Ω_0)
Spherical	positive	closed	$\rho_0 > \rho_c$	$\Omega_0 > 1$
Flat	zero	flat	$\rho_0 = \rho_c$	$\Omega_0 = 1$
Hyperbolic	negative	open	$\rho_0 < \rho_c$	$\Omega_0 < 1$

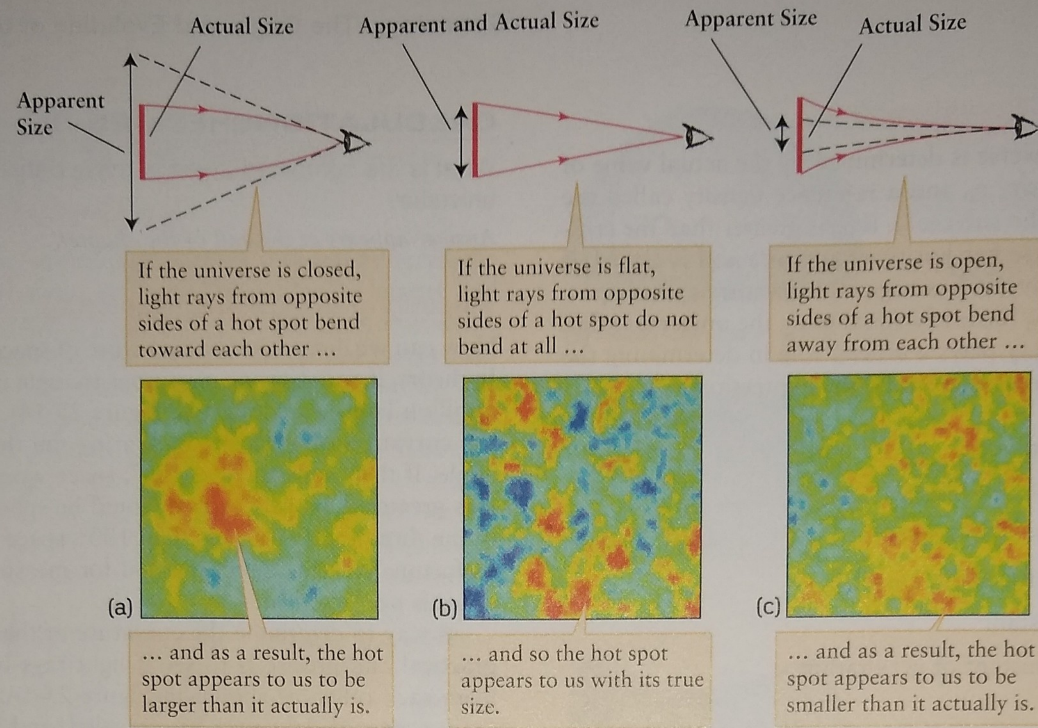


FIGURE 25-15 R I V U X G

The Cosmic Microwave Background and the Curvature of Space Temperature variations in the early universe appear as "hot spots" in the cosmic microwave background. The apparent size of these spots depends on the curvature of space. (The BOOMERANG Group, University of California, Santa Barbara)

As Table 25-1 shows, once we know the curvature of the universe, we can determine the density parameter Ω_0 and hence the combined average mass density ρ_0. By analyzing the data shown in Figure 25-13, astrophysicists find that $\Omega_0 = 1.0$ with an uncertainty of about 2%. In other words, ρ_0 is within 2% of the critical density ρ_c.

The flatness of the universe poses a major dilemma: Even if you include dark matter, there is not enough matter to make the universe flat. We saw in Section 25-5 that the average mass density of matter in the universe, ρ_m, is 2.4×10^{-27} kg/m³. This density is only 0.24 of the critical density ρ_c. We can express this ratio in terms of the **matter density parameter** Ω_m (say "omega sub em"), equal to the ratio of ρ_m to the critical density:

$$\Omega_m = \frac{\rho_m}{\rho_c} = 0.24$$

If matter and radiation were all there is in the universe, the combined average mass density ρ_0 would be equal to ρ_m (plus a tiny contribution from radiation, which we can neglect because the average mass density of radiation is only about 0.02% that of matter). Then the density parameter Ω_0 would be equal to Ω_m—that is, equal to 0.24—and the universe would be open. But the temperature variations in the cosmic microwave background clearly show that the universe is either flat or very nearly so. These variations also show that the density parameter Ω_0, which includes the effects of *all* kinds of matter and energy, is equal to 1.0. In other words, radiation and matter, including dark matter, together account for only 24% of the total density of the universe! The dilemma is to account for the rest of the density.

CONCEPTCHECK 25-12

In a closed universe, a 1-meter stick is moved from Earth out to a specific location in the distant cosmos. Assuming it could be observed from Earth, would the stick appear larger, smaller, or the same in size than in a flat universe at that same distance?

Answer appears at the end of the chapter.

Dark Energy

The geometry of space reveals that the universe is filled with dark energy

The source of the missing energy density must be some form of energy that we cannot detect through the various gravitational effects that astronomers use to detect dark matter. The missing energy density also does not appear to emit detectable radiation of any kind, so we cannot directly detect it with light. With these properties in mind, we refer to this mysterious energy as **dark energy**.

Just as we express the average density of matter and radiation by the matter density parameter Ω_m, we can express the average density of dark energy in terms of the **dark energy density parameter** Ω_Λ (say "omega sub lambda"). This parameter is equal to the average mass density of dark energy, ρ_Λ, divided by the critical density ρ_c:

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c}$$

We can determine the value of Ω_Λ by noting that the combined average mass density ρ_0 must be the sum of the average mass densities of matter, radiation, and dark energy. As we have seen, the contribution of radiation is so small that we can ignore it, so we have

$$\rho_0 = \rho_m + \rho_\Lambda$$

If we divide this through by the critical density ρ_c, we obtain

$$\Omega_0 = \Omega_m + \Omega_\Lambda$$

That is, the density parameter Ω_0 is the sum of the matter density parameter Ω_m and the dark energy density parameter Ω_Λ. Solving for Ω_Λ, we find

$$\Omega_\Lambda = \Omega_0 - \Omega_m$$

Since Ω_0 is close to 1.0 and Ω_m is 0.24, we conclude that Ω_Λ must be 1.0 − 0.24 = 0.76. Thus, whatever dark energy is, it accounts for 76% (about three-quarters) of the energy content of the universe!

To put the dark energy density into context, consider the kinetic energy of a jumping flea. The flea's kinetic energy is very small (about the same amount of electrical energy used in turning on a single LED light for one ten-millionth of a second). Since an energy density is the amount of energy contained within a certain volume, to put the dark energy density into context, we also need to indicate a corresponding volume. Thus, *the dark energy density is equivalent to a single jumping flea within the volume of a big football stadium* (dome and all). Since most of the universe is devoid of matter, this energy density, filling all of space, ends up being the dominant form of energy in our universe. (The CMB contains many photons, but the expansion of space has significantly lowered their energy and their density.)

The concept of dark energy is actually due to Einstein. When he proposed the existence of a cosmological constant, he was suggesting that the universe is filled with a form of energy that by itself tends to make the universe expand (see Section 25-1). Unlike gravity, which tends to make objects attract, the energy associated with a cosmological constant would provide a form of "antigravity." Hence, it would not be detected in the same way as matter. (The subscript Λ in the symbol for the dark energy density parameter pays homage to the symbol that Einstein chose for the cosmological constant.)

If dark energy is in fact due to a cosmological constant, the value of this constant must be far larger than Einstein suggested. This change in the constant is needed if we are to explain why Ω_Λ has a large value of 0.76. If Einstein felt he erred by introducing the idea of a cosmological constant, his error was giving it too small a value!

These ideas concerning dark energy are extraordinary, and extraordinary claims require extraordinary evidence to confirm them. As we will see in the next section, another way to measure dark energy is to examine how the rate of expansion of the universe has evolved over the eons.

CONCEPTCHECK 25-13

If we do not know what makes up dark energy, how can we estimate its energy density?

Answer appears at the end of the chapter.

25-7 Observations of distant supernovae reveal that we live in an accelerating universe

We have seen that the universe is expanding. But does the rate of expansion stay the same? Because there is matter in the universe, and because gravity tends to pull the bits of matter in the universe toward one another, we would expect that the expansion should slow down with time. (In the same way, a cannonball shot upward from the surface of Earth will slow down as it ascends because of Earth's gravitational pull.) If there is a cosmological constant, however, its associated dark energy will exert an outward pressure that tends to accelerate the expansion. Which of these effects is more important?

Modeling the Expansion History of the Universe

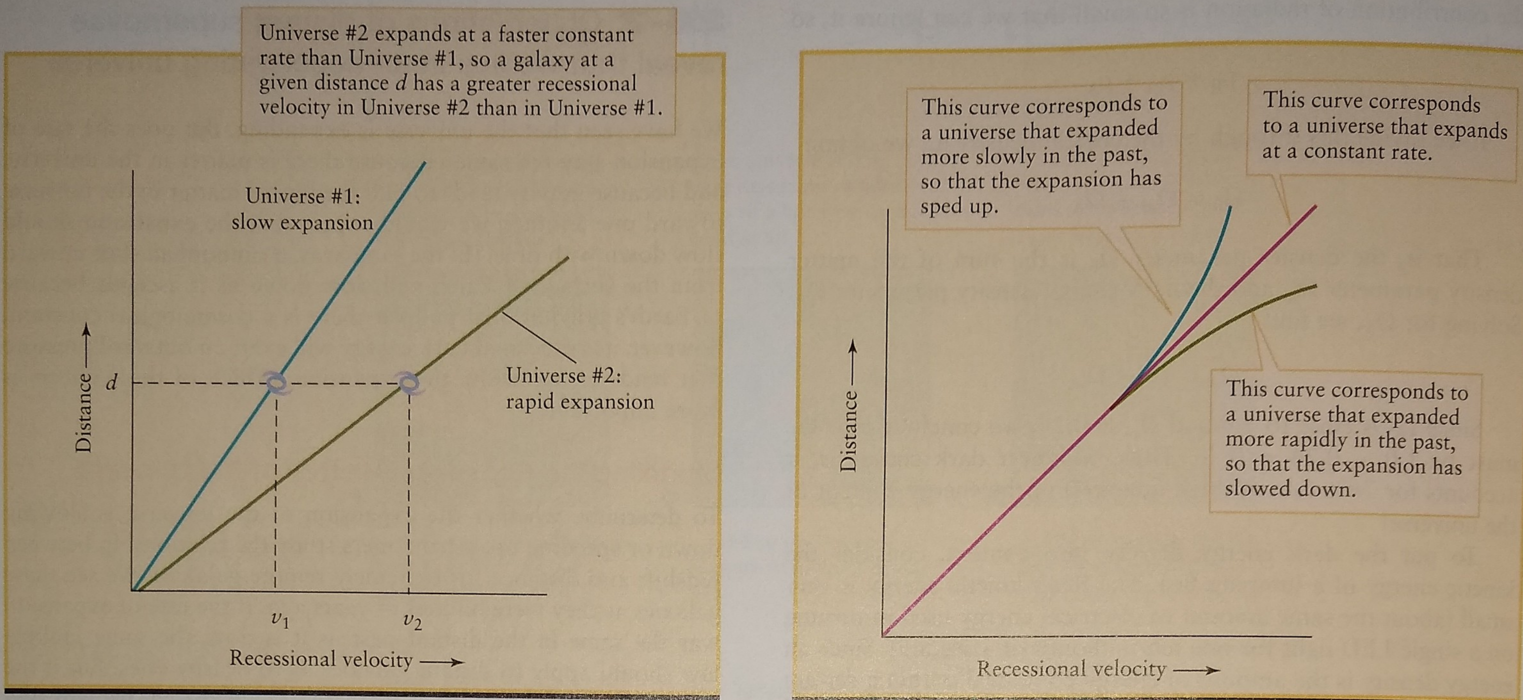
To determine whether the expansion of the universe is slowing down or speeding up, astronomers study the relationship between redshift and distance for extremely remote galaxies. We see these galaxies as they were billions of years ago. If the rate of expansion was the same in the distant past as it is now, the same Hubble law should apply to distant galaxies as to nearby ones. But if the rate of expansion has either increased or decreased, we will find important deviations from the Hubble law.

To see how astronomers approach this problem, first imagine two different parallel universes. Both Universe #1 and Universe #2 are expanding at constant rates, so for both universes there is a direct proportion between recessional velocity v and distance d as expressed by the Hubble law $v = H_0 d$. Hence, a graph of distance versus recessional velocity for either universe is a straight line, as Figure 25-16a shows. The only difference is that Universe #1 is expanding at a slower rate than Universe #2. Hence, a galaxy at a certain distance from Earth in Universe #1 will have a slower recessional velocity than a galaxy at the same distance from Earth in Universe #2. As a result, the graph of distance versus recessional velocity for slowly expanding Universe #1 (shown in blue) has a steeper slope than the graph for rapidly expanding Universe #2 (shown in green). Keep this observation in mind: A slower expansion means a steeper slope on a graph of distance versus recessional velocity.

Now consider *our* universe and allow for the possibility that the expansion rate may change over time. If we observe very remote galaxies, we are seeing them as they were in the remote past. If the expansion of the universe in the remote past was slower or faster than it is now, the slope of the graph of distance versus recessional velocity will be different for those remote galaxies. If the expansion was slower, then the slope will be steeper for distant galaxies (shown in blue in Figure 25-16b); if the expansion was faster, the slope will be shallower for distant galaxies (shown in green in Figure 25-16b). In either case, there will be a deviation from the straight-line Hubble law (shown in red in Figure 25-16b).

Measuring Ancient Expansion with Type Ia Supernovae

Which of the possibilities shown in Figure 25-16b represents the actual history of the expansion of our universe? In Section 23-5 we looked at the observed relationship between distance and



(a) Two universes with different expansion rates

(b) Possible expansion histories of the universe

FIGURE 25-16

Varying Rates of Cosmic Expansion (a) Imagine two universes, #1 and #2. Each expands at its own constant rate. For a galaxy at a given distance, the recessional velocity will be greater in the more rapidly expanding universe. Hence, the graph of distance *d* versus recessional velocity *v* will have a shallower slope for the rapidly expanding universe and a steeper slope for the slowly expanding one. (b) If the rate of expansion of our universe was more rapid in the distant past, corresponding to remote distances, the graph of *d* versus *v* will have a shallower slope for large distances (green curve). If the expansion rate was slower in the distant past, the graph will have a steeper slope for large distances (blue curve).

recessional velocity for galaxies. Figure 23-16 is a plot of some representative data. The data points appear to lie along a straight line, suggesting that the rate of cosmological expansion has not changed. (Figure 23-16 is actually a graph of recessional velocity versus distance, not the other way around. But a straight line on one kind of graph will be a straight line on the other, because in either case there is a direct proportion between the two quantities being graphed.) However, the graph in Figure 23-16 was based on measurements of galaxies no farther than 400 Mpc (1.3 billion ly) from Earth, which means we are looking only 1.3 billion years into the past. The straightness of the line in Figure 23-16 means only that the expansion of the universe has been relatively constant over the past 1.3 billion years—only 10% of the age of the universe and a relatively brief interval on the cosmic scale.

Now suppose that you were to measure the redshifts and distances of galaxies *several* billion light-years from Earth. The light from these galaxies has taken billions of years to arrive at your telescope, so your measurements will reveal how fast the universe was expanding billions of years ago. To determine the expansion, we need a technique that will allow us to find the distances to these very remote galaxies. We saw in Section 23-4 that one way to determine distances is to identify Type Ia supernovae in such galaxies. These supernovae are among the most luminous objects in the universe, and hence can be detected even at extremely large distances (see Figure 23-14). The maximum brightness of a supernova tells astronomers its distance through the inverse-square law for light, and the redshift of the supernova's spectrum tells them its recessional velocity. As an example, the image that opens this chapter shows Type Ia supernovae with redshifts $z = 1.010$, 1.230, and 1.390, corresponding to recessional velocities of 60%, 67%, and 70% of the speed of light. We see these supernovae as they were 7.7 to 9.0 billion years ago, when the universe was less than half of its present age.

In 1998, two large research groups—the Supernova Cosmology Project, led by Saul Perlmutter of Lawrence Berkeley National Laboratory, and the High-Z Supernova Search Team, led by Brian Schmidt of the Mount Stromlo and Siding Springs Observatories in Australia—reported their results from a survey of Type Ia supernovae in galaxies at redshifts of 0.2 or greater, corresponding to distances beyond 750 Mpc (2.4 billion ly). Figure 25-17 shows some of their data, along with more recent observations, on a graph of apparent magnitude versus redshift. Recall that a greater apparent magnitude corresponds to a dimmer supernova (see Section 17-3), which means that the supernova is more distant. A greater redshift implies a greater recessional velocity. Hence, this graph is basically the same as those in Figure 25-16 (distance versus recessional velocity).

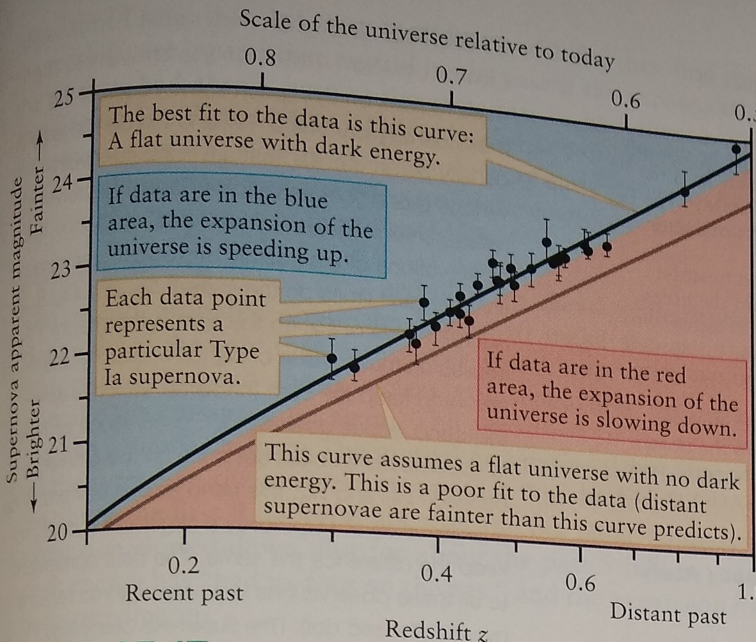


FIGURE 25-17

The Hubble Diagram for Distant Supernovae This graph shows apparent magnitude versus redshift for supernovae in distant galaxies. The greater the apparent magnitude, the dimmer the supernova and the greater the distance to it and its host galaxy. If the expansion of the universe is speeding up, the data will lie in the blue area; if it is slowing down, the data will lie in the red area. The data show that the expansion is in fact speeding up. (The Supernova Cosmology Project/S. Perlmutter)

To interpret these results, we need guidance from **relativistic cosmology.** This field provides a theoretical description of the universe and its expansion, based on Einstein's general theory of relativity, and was developed in the 1920s by Alexander Friedmann in Russia, Georges Lemaître in France, and Willem de Sitter in the Netherlands. Given values of the mass density parameter Ω_m and the dark energy density parameter Ω_Λ, cosmologists can use the equations of relativistic cosmology to predict how the expansion rate of the universe should change over time. Such predictions can be expressed as curves on a graph of distance versus redshift such as Figure 25-17.

The lower, gray curve in Figure 25-17 shows what would be expected in a flat universe with $\Omega_0 = 1.00$ but with no dark energy, so that $\Omega_\Lambda = 0$ and $\Omega_m = \Omega_0$ (that is, the density parameter is due to matter and radiation alone). In this model, and in fact in any model whose curve lies in the red area in Figure 25-17, the absence of dark energy means that gravitational attraction between galaxies would cause the expansion of the universe to slow down with time. Hence, the expansion rate would have been greater in the past (compare with the green curve in Figure 25-16b).

In fact, the data points in Figure 25-17 are almost all in the *blue* region of the graph, and agree very well with the curve shown in black. This curve also assumes a flat universe, but with an amount of dark energy consistent with the results from the cosmic microwave background ($\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$, $\Omega_0 = \Omega_m + \Omega_\Lambda = 1.00$). In this model, and indeed in any model whose curve lies in the blue region of Figure 25-17, dark energy has made the expansion of the universe speed up over time. Hence, the expansion of the universe was slower in the distant past, which means that we live in an *accelerating* universe.

Just like the blue curve in Figure 25-16b, the data in Figure 25-17 show that supernovae of a certain brightness (and hence a given distance) have smaller redshifts (and hence smaller recessional velocities) than would be the case if the expansion rate had always been the same. These data provide compelling evidence of the existence of dark energy.

Roughly speaking, the data in Figure 25-17 indicate the relative importance of dark energy (which tends to make the expansion speed up) and gravitational attraction between galaxies (which tends to make the attraction slow down). Thus, these data tell us about the *difference* between the values of the dark energy density parameter Ω_Λ and the matter density parameter Ω_m. By contrast, measurements of the cosmic microwave background (Section 25-6) give information about Ω_0, equal to the *sum* of Ω_Λ and Ω_m. Observations of galaxy clusters (Section 25-5) set limits on the value of Ω_m by itself (which includes visible and dark matter). By combining these three very different kinds of observations as shown in Figure 25-18, we can set more stringent limits on both Ω_Λ and Ω_m.

Taken together and combined with other observations, all these data suggest the following values.

$$\Omega_m = 0.241 \pm 0.034$$

$$\Omega_\Lambda = 0.759 \pm 0.034$$

$$\Omega_0 = \Omega_m + \Omega_\Lambda = 1.02 \pm 0.02$$

In each case, the number after the ± sign is the uncertainty in the value.

> Dark energy became the dominant form of energy in the universe about the same time that our solar system formed

This collection of numbers points to a radically different model of the universe from what was suspected just a few years ago. In the 1980s there was no compelling evidence for an accelerating expansion of the universe, so it was widely assumed that $\Omega_\Lambda = 0$. Evidence from distant ga[laxies] suggested a flat universe, so it was presumed that $\Omega_m =$ [1.] Figure 25-18 shows that modern data rule out this model.

The model we are left with is one in which the universe is su[f]fused with a curious dark energy due to a cosmological constan[t]. Unlike matter or radiation, whose average densities decrease as th[e] universe expands and thins out, the average density of this da[rk] energy remains constant throughout the history of the univer[se] (Figure 25-19). The dark energy was relatively unimportant ov[er] most of the early history of the universe. Today, however, the densi[ty] of dark energy is greater than that of matter (Ω_Λ is greater than Ω_m). In other words, we live in a **dark-energy–dominated universe.**

CONCEPTCHECK 25-14

What assumption must one make about Type Ia supernovae [in] order to use them to measure distances to galaxies?

Answer appears at the end of the chapter.

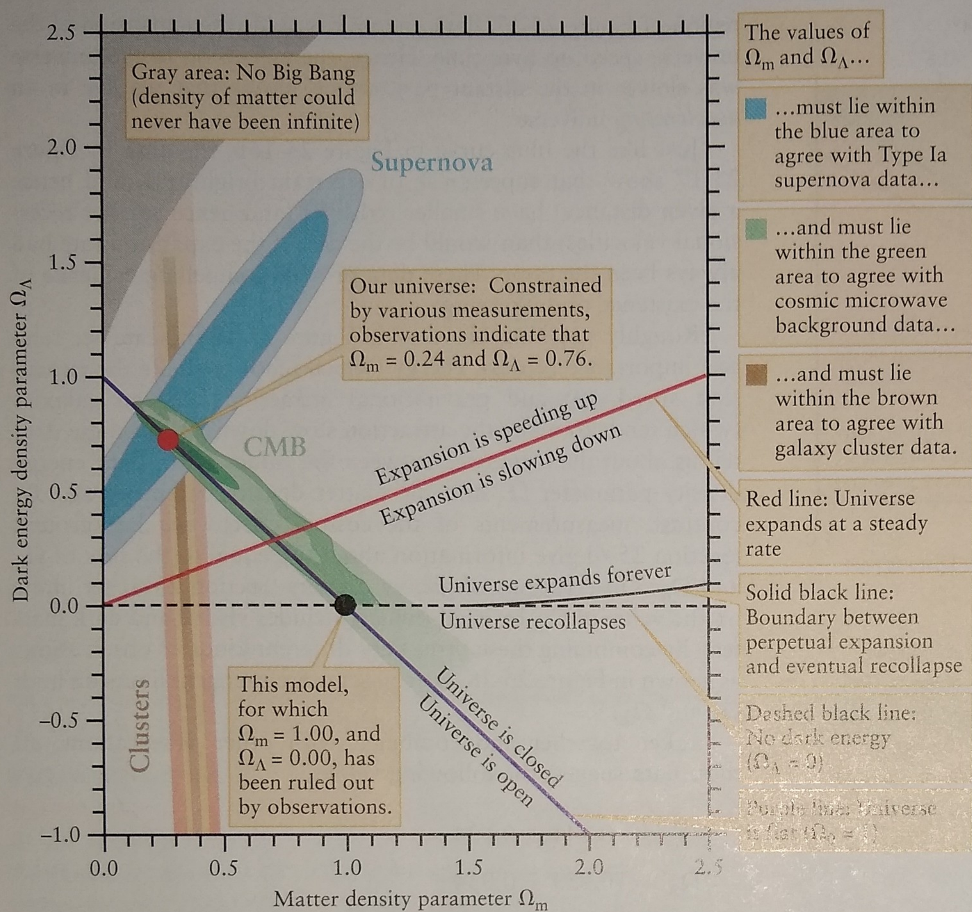
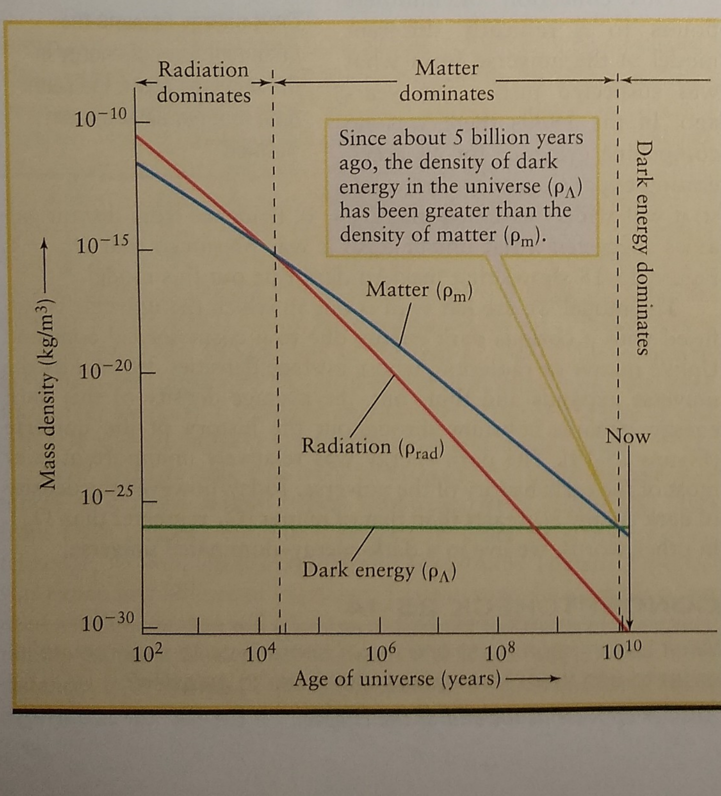


FIGURE 25-18

Limits on the Nature of the Universe The three regions on this graph show values of the mass density parameter Ω_m and the dark energy density parameter Ω_Λ that are consistent with various types of observations. Galaxy cluster measurements (in brown) set limits on Ω_m. Observations of the cosmic microwave background (in green) set limits on the sum of Ω_m and Ω_Λ: A larger value of Ω_m (to the right in the graph) implies a smaller value of Ω_Λ (downward in the graph) to keep the sum the same, which is why this band slopes downward. Observations of Type Ia supernovae (in blue) set limits on the difference between Ω_m and Ω_Λ; this band slopes upward since a larger value of Ω_m implies a larger value of Ω_Λ to keep the difference the same. The best agreement to all these observations is where all three regions overlap (the red dot). (The Supernova Cosmology Project/S. Perlmutter)



Cosmic Expansion: From Slowing Down to Speeding Up

ANIMATION 25-4 ANIMATION 25-5

As Figure 25-19 shows, the dominance of dark energy is a relatively recent development in the history of the universe. Prior to about 5 billion years ago, the density of matter should have been greater than that of dark energy. Hence, we would expect that up until about 5 billion years ago, the expansion of the universe should have been slowing down rather than speeding up. Recently, astronomers have found evidence of this picture by using the Hubble Space Telescope to observe extremely distant Type Ia supernovae with redshifts z greater than 1. (The image that opens this chapter shows three of these supernovae.) When astronomers compare the distance to these supernovae

FIGURE 25-19

The Evolution of Density, Revisited The average mass density of matter, ρ_m, and the average mass density of radiation, ρ_{rad}, both decrease as the universe expands and becomes more tenuous. But if the dark energy is due to a cosmological constant, its average mass density ρ_Λ remains constant. In this model, our universe became dominated by dark energy about 5 billion years ago.

(determined from their brightness) to their redshifts, they find that the redshifts are *greater* than would be the case if the expansion of the universe had always been at the same rate or had always been speeding up (see Figure 25-16). This is just what would be expected if the expansion was slowing down in the very early universe. After about 5 billion years ago, the effects of dark energy became dominant and the expansion began to speed up.

ANALOGY If you see a red light up ahead while driving, you would probably apply the brakes to make the car slow down. But if the light then turns green before your car comes to a stop, and the road ahead is clear, you would step on the gas to make the car speed up again. The expansion of the universe has had a similar history. The mutual gravitational attraction of all the matter in the universe means that "the brakes were on" for about the first 9 billion years after the Big Bang, so that the expansion slowed down. But for about the past 5 billion years, dark energy has "had its foot on the gas," and the expansion has been speeding up.

So far, observations of distant supernovae support dark energy that is described by a cosmological constant. If dark energy truly is a cosmological constant, the density of dark energy will continue to remain constant, as shown in Figure 25-19. Due to the effects of this dark energy, the universe will keep on expanding forever, and the rate of expansion will continue to accelerate. Eventually, some 30 billion years from now, the universe will have expanded so much that only a thousand or so of the nearest galaxies will still be visible. The billions of other galaxies that we can observe today will have moved so far away from us that their light will have faded to invisibility. Furthermore, they will be moving away from us so rapidly that what light we do receive from them will have been redshifted out of the visible range.

There may be other explanations for dark energy besides a cosmological constant, however. Several physicists have proposed a type of dark energy whose density decreases slowly as the universe expands. Depending on how the density of dark energy evolves over time, the universe could continue to expand or could eventually recollapse on itself. Future observations, including space-based measurements of both the cosmic background radiation and of Type Ia supernovae, should help resolve the nature of the mysterious dark energy.

What Is Dark Energy?

While the evidence for an accelerating universe is strong enough that its discoverers were awarded the Nobel Prize in Physics in 2011, the nature of the dark energy implied by this acceleration is far from clear. The physical interpretation of the cosmological constant is that there is an energy associated with space itself. With a cosmological constant, the more space there is, the more energy there is. In other words, as the universe expands, the additional space leads to more energy. Just as the energy content in the universe determines its shape (Section 25-6), the energy content can also cause the universe to accelerate its expansion, and this is what dark energy is doing. But, how does energy arise from seemingly empty space?

The answer might come from **virtual particle pairs**—imperceptible particles made of matter and antimatter. As mentioned in Section 21-9, quantum physics reveals that seemingly empty space is not so empty after all. Everywhere, at all times, virtual particle pairs pop up from nothing and then disappear again on very short timescales. While the virtual particles themselves are not directly observable, the phenomenon is real and secondary effects of the virtual particles have been observed. In fact, virtual particle effects between microscopic nanotechnology devices are strong enough that this phenomenon can produce practical problems—forces that cause some devices to clump together. In Chapter 26, we will also discuss virtual particles for their possible role in the early universe.

Because virtual particles appear in the otherwise empty "vacuum" of space, they are called vacuum fluctuations. Overall, the effect of virtual particles, or vacuum fluctuations, is to produce an energy associated with space itself. This seems to be just what is needed to produce a cosmological constant. However, there is a big problem with this explanation for dark energy. When the effects of virtual particles are calculated, they predict a cosmological constant that is 100 orders of magnitude larger than what is actually observed; that number has a one with a *hundred zeroes* after it! With such a large numerical discrepancy between theory and observation, our current understanding of virtual particles and vacuum fluctuations cannot explain dark energy. Perhaps a modification of the vacuum fluctuation model can explain dark energy, but each theoretical modification also introduces new problems.

There are other theories offered to explain dark energy. Some propose that Einstein's general theory of relativity needs modifying on very large scales. Others propose that we are in a special part of the universe that only gives the appearance of accelerated expansion, so that there is actually no dark energy at all. However, each theory has its own difficulties and no explanation has gained wide acceptance. While the observations march forward, they are difficult, and dark energy is likely to remain one of the universe's greatest mysteries for some time to come.

25-8 Primordial sound waves help reveal the character of the universe

We have seen how studying the "hot spots" in the cosmic background radiation reveals that we live in a flat universe. In fact, temperature variations reveal more: They give us a window on conditions in the early universe, and actually help us pin down the values of other important quantities such as the Hubble constant and the density of matter in the universe. The key to extracting this additional information from the cosmic background radiation is recognizing that the hot and cold spots in a map such as Figure 25-13 actually result from sound waves.

Sound Waves in the Early Universe

Sound waves can travel in gases and fluids of all kinds. Sound waves in air are used in human speech and hearing, while whales communicate using high-frequency underwater clicks and whistles. If you could take a snapshot of a sound wave, you would see that at any moment there are some regions, called **compressions**, where the gas or fluid is squeezed together, and other regions, called **rarefactions**, where the gas or fluid is thinned out or rarefied (Figure 25-20).

Immense sound waves in the early universe left their imprint as variations in the cosmic microwave background

There would also have been sound waves in the early universe before recombination. During the first 380,000 years after the Big Bang, the universe was filled with a fluidlike medium composed primarily of photons, electrons, and protons, with a density more than 10^9 times greater than that of our present-day universe. Just as water molecules in a glass of water collide with each other, photons and particles collided frequently with each other in this primordial fluid, triggering random sound waves with compressions and rarefactions.

Before discussing the sound waves in more depth, it is worth revisiting the relationship discussed in Section 25-5 between temperature and density variations. Because there was more mass in a compression than in a rarefaction, photons emerging from a compression experienced a greater gravitational redshift than did photons emerging from a rarefaction (see Section 21-2). As a result, the light from a compression is shifted to slightly longer wavelengths. We saw in Sections 5-3 and 5-4 that a blackbody spectrum dominated by longer wavelengths corresponds to a lower blackbody temperature (see Figure 5-11). Hence, we see compressions as the blue cold spots in Figure 25-13, and we see rarefactions as the red hot spots. The overall pattern of cold and hot spots is thus a record of the density variations due to sound waves that were present just as the universe became transparent, some 380,000 years after the Big Bang. From the denser compressions arose our present-day population of galaxies.

The nature of a sound wave depends on the material through which it passes. For example, sound waves travel faster in helium than they do in air (because helium is less dense) and faster still in water (which, while denser than air, is much more resistant to compression). So, by studying the primordial sound waves recorded in Figure 25-13, we can learn about the properties of the fluid that made up the early universe. These properties include the average densities of matter and dark energy in the fluid, as well as the value of the Hubble constant (which helps determine how rapidly the fluid was expanding and thinning out as the universe expanded). We can also determine the age of the universe at the time that the cosmic background radiation was emitted, since this determines the maximum size to which a hot spot (rarefaction) or cold spot (compression) could have grown since the Big Bang.

Figure 25-21 shows an important way in which astronomers systematize their data about hot and cold spots in the cosmic background radiation. This graph shows the number of observed hot or cold spots of different angular sizes, with larger spots on the left and smaller spots on the right. The presence of peaks in the graph shows that spots of certain sizes are more common than others. The largest peak tells us that the predominant angular size is about 1°, which corresponds to a region of compression or rarefaction that was about a million (10^6) light-years across at the time of recombination at $z = 1100$. (By contrast, the compressions and rarefactions in the sound waves most used in speech are a few meters across.) Since then the universe has expanded by a factor of about 1100, so that same region is now about a billion (10^9) light-years across.

The peaks in Figure 25-21 tell us the size scales that matter formed into clumps, and these over-dense regions were the seeds of structure formation. As predicted, we see the imprint of these early sound waves in today's distribution of mass. Figure 25-22 illustrates this evolution from variations in the CMB to the distribution of galaxies.

Different cosmological models predict different shapes for the curve shown in Figure 25-21. Astronomers determine the best model by seeing which one gives a curve that best fits the data points. For example, the peak of the curve at an angular size of 1° is just what would be expected for a flat universe with $\Omega_0 = 1$. It should be emphasized that Figure 25-21 represents an enormous success for Big Bang cosmology in making detailed predictions, matched by observations, for features covering the entire sky—some only fractions of a degree wide and others covering tens of degrees. By fitting detailed models to the CMB data, the temperature fluctuations reveal the Hubble constant, the combined (total) energy density parameter, the ordinary matter density, and the dark energy density. Table 25-2 summarizes the results of a flat-universe model that yields the particular curve shown in Figure 25-21.

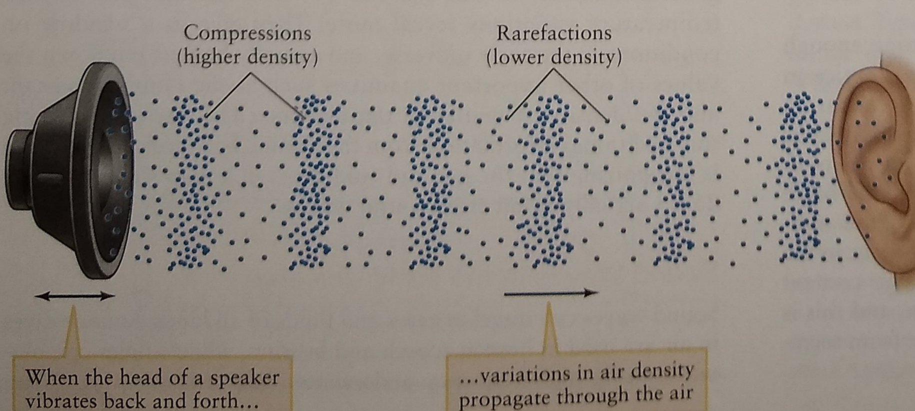


FIGURE 25-20
Snapshot of a Sound Wave When the head of a speaker oscillates back and forth, higher-density compressions are created that propagate through the air. The sound from clapping your hands is produced in a similar way, but for a shorter length of time. When a sound wave enters a human ear, the air next to the eardrum is alternately compressed and rarefied, which makes the eardrum flex back and forth. This flexing is translated into an electrical signal that is sent to the brain. Sound waves produced shortly after the Big Bang (inaudible to the human ear) also produced variations in the density of matter throughout the universe.

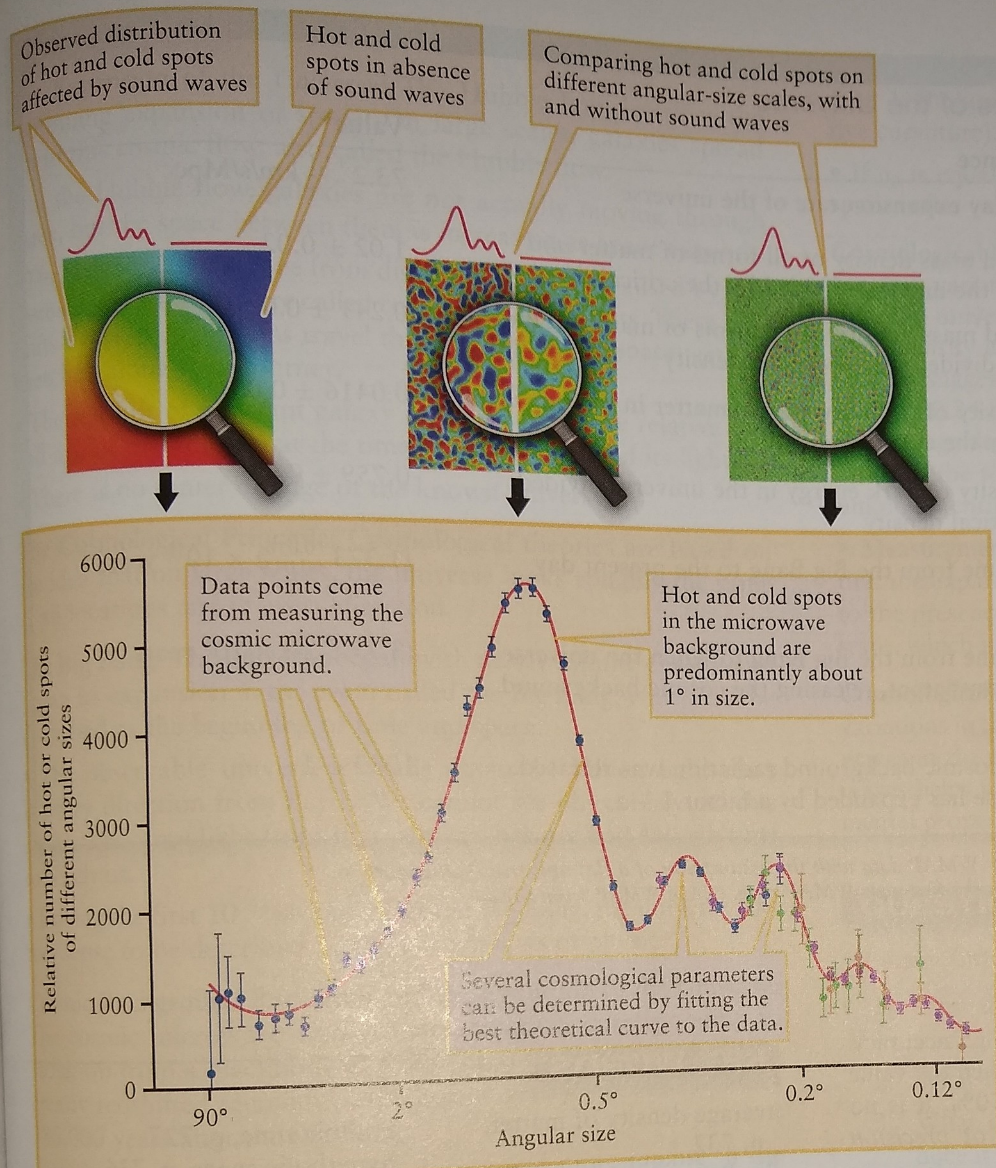


FIGURE 25-21

Sound Waves in the Early Universe Top panel: At three different angular sizes (90°, 1°, and 0.25°) a comparison is made between the observed temperature variations in the cosmic microwave background resulting from sound waves and the temperature variations in a hypothetical universe with no sound waves. Sound waves affect the distribution of temperature fluctuations, but do not entirely create them. Bottom panel: Observations of the cosmic background radiation show that hot and cold spots of certain angular sizes are more common than others. Matching a model that describes these observations (the red curve) helps to determine the values of important cosmological parameters. Most of the data shown here are from WMAP; the data for the smallest angles (at the right of the graph) come from the CBI detector in the Chilean Andes and the ACBAR and BOOMERANG detectors at the south pole. (top panel: NASA/WMAP Science Team; graph: Adapted from "The Hubble Constant," Wendy L. Freedman and Barry F. Madore, Carnegie Observatories)

Our understanding of the universe as a whole has increa tremendously over the past several years. We have found comp ling evidence that dark energy exists and that it is the domin form of energy in the universe. Studies of supernovae, gala clusters, and the cosmic background radiation have provided with so much high-quality data that we can now express the

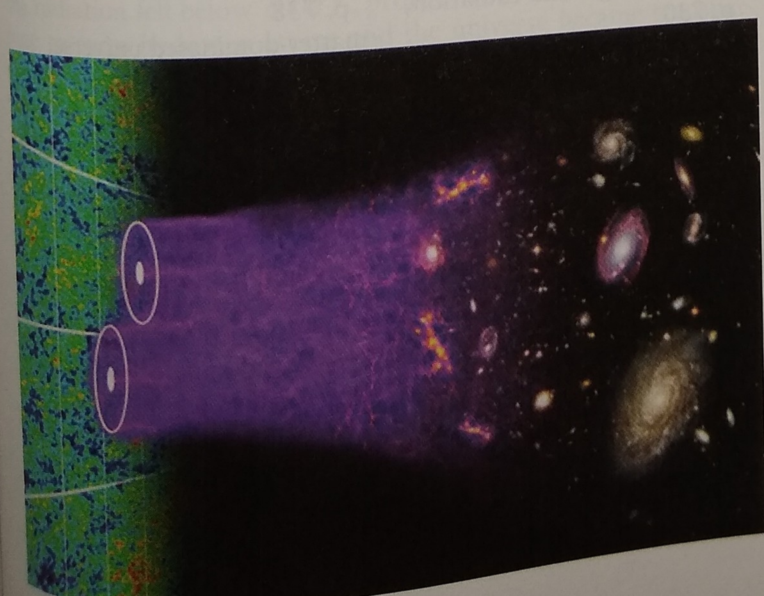


FIGURE 25-22

Structure Evolution from Sound Waves This illustration shows the evolution of early density variations seen in the CMB to the present-day distribution of galaxies. The size scales of the resulting variations are much larger than galaxies or clusters, and the variations show up as filaments ar voids traced out by the distribution of superclusters of galaxies. The Baryo Oscillation Spectroscopic Survey (BOSS) has observed these variations at their predicted size scale of around 150 Mpc. (Illustration courtesy of Chris Bla and Sam Moorfield)

TABLE 25-2 Some Key Properties of the Universe

Quantity	Significance	Value*
Hubble constant, H_0	Present-day expansion rate of the universe	$73.2^{+3.1}_{-3.2}$ km/s/Mpc
Density parameter, Ω_0	Combined mass density of all forms of matter *and* energy in the universe divided by the critical density	1.02 ± 0.02
Matter density parameter, Ω_m	Combined mass density of all forms of matter in the universe, divided by the critical density	0.241 ± 0.034
Density parameter for ordinary matter, Ω_b	Mass density of ordinary atomic matter in the universe divided by the critical density	0.0416 ± 0.001
Dark energy density parameter, Ω_Λ	Mass density of dark energy in the universe divided by the critical density	0.759 ± 0.034
Age of the universe, T_0	Elapsed time from the Big Bang to the present day	$(1.373^{+0.016}_{-0.015}) \times 10^{10}$ years
Age of the universe at the time of recombination	Elapsed time from the Big Bang to when the universe became transparent, releasing the cosmic background radiation	$(3.79^{+0.08}_{-0.07}) \times 10^{5}$ years
Redshift z at the time of recombination	Since the cosmic background radiation was released, the universe has expanded by a factor $1 + z$	1089 ± 1

**Values for H_0, Ω_m, Ω_b, and T_0 are based on the three-year WMAP data with the assumption of a flat universe. Values for the time and redshift of recombination and for Ω_0 are from the first-year WMAP data.* (NASA/WMAP Science Team)

parameters of the universe (Table 25-2) with very high accuracy. When we look back to the situation in the 1980s, when the value of the Hubble constant was uncertain by at least 50%, it is no exaggeration to say that we have entered an age of *precision* cosmology.

Yet many questions remain unanswered. What is the nature of dark matter? What actually is dark energy? Together, the unknown nature of dark matter and dark energy indicate that we do not understand about 96% of the energy content in our universe. Can either of these mysterious entities be detected and studied in the laboratory? These and other questions will continue to occupy cosmologists for many years to come.

CONCEPTCHECK 25-15

Consider Figure 25-21. The colorful pictures along the top compare how temperature fluctuations appear in the presence of sound waves with how they would appear in the absence of sound waves. On what size scale are the temperature fluctuations most affected by the presence of sound waves in the early universe?

CALCULATIONCHECK 25-4

Consult Table 25-2. What percent of the energy content of the universe comes from ordinary matter (such as the matter making planets and stars)? What percent comes from dark energy?

Answers appear at the end of the chapter.

KEY WORDS

average density of matter, p. 732
Big Bang, p. 727
closed universe, p. 736
combined average mass density, p. 736
compression, p. 744
cosmic background radiation, p. 730
cosmic light horizon, p. 729
cosmic microwave background (CMB), p. 730
cosmological constant, p. 722
cosmological principle, p. 727
cosmological redshift, p. 726
cosmology, p. 722
critical density, p. 737
dark energy, p. 738
dark energy density parameter, p. 738
dark-energy–dominated universe, p. 741
density parameter, p. 737
era of recombination, p. 734
flat space, p. 736
homogeneous, p. 727
Hubble time, p. 727
hyperbolic space, p. 736
isotropic, p. 727
lookback time, p. 726
mass density of radiation, p. 732
matter density parameter, p. 738
matter-dominated universe, p. 733
negative curvature, p. 736
observable universe, p. 729
Olbers's paradox, p. 722
open universe, p. 736
Planck time, p. 729
plasma, p. 734
positive curvature, p. 736
primordial fireball, p. 734
radiation-dominated universe, p. 733
rarefaction, p. 744
relativistic cosmology, p. 741
spherical space, p. 736
virtual particle pairs, p. 743
zero curvature, p. 736

KEY IDEAS

The Expansion of the Universe: The Hubble law describes the continuing expansion of space. On large scales, galaxies spread out in this cosmic flow, also called the Hubble flow.

- In the Hubble flow, galaxies are not actually moving through space, but the space between them is increasing as space expands.
- The redshifts that we see from distant galaxies are caused by this cosmic expansion and are called cosmological redshifts. These redshifts develop as photons travel through expanding space, getting stretched along their journey.
- The redshift of a distant galaxy is a measure of the relative size and age of the universe at the time the galaxy emitted its light.
- There is no center or edge of the known universe.

The Cosmological Principle: Cosmological theories are based on the idea that on large scales, the universe looks roughly the same at all locations and in every direction.

The Big Bang: The universe began with nearly infinite density and began its expansion in the event called the Big Bang, which can be described as the beginning of time and space.

- The observable universe extends about 14 billion light-years in every direction from Earth. We cannot see objects beyond this distance because light from these objects has not had enough time to reach us.
- During the first 10^{-43} second after the Big Bang, the universe was too dense to be described by the known laws of physics.

Cosmic Background Radiation and the Evolution of the Universe: The cosmic microwave background radiation, corresponding to radiation from a blackbody at a temperature of nearly 3 K, is the greatly redshifted remnant of the hot universe as it existed about 380,000 years after the Big Bang.

- The background radiation was hotter and more intense in the past. During the first 380,000 years of the universe, radiation and matter formed an opaque plasma called the primordial fireball.
- Light from this early era gets scattered before it can carry images to us, but then there is an abrupt change. When the temperature of the radiation fell below 3000 K, protons and electrons could combine to form hydrogen atoms and the universe became transparent. We can look all the way back to this transition, which is what we see in images of the cosmic microwave background radiation.
- The universal abundance of helium is much more than stars can produce. Most helium was produced by thermonuclear reactions occurring throughout the universe during its first few minutes. It was the high temperatures required for these thermonuclear reactions that led to the prediction of the cosmic microwave background radiation, which was much hotter in the early universe.

The Geometry of the Universe: The curvature of the universe as a whole depends on how the combined average mass density ρ_0 compares to a critical density ρ_c. Due to the equivalence of mass and energy, ρ_0 also includes contributions from dark energy.

- If ρ_0 is greater than ρ_c, the density parameter Ω_0 has a value greater than 1, the universe is closed, and space is spherical (with positive curvature).
- If ρ_0 is less than ρ_c, the density parameter Ω_0 has a value les than 1, the universe is open, and space is hyperbolic (with nega tive curvature).
- If ρ_0 is equal to ρ_c, the density parameter Ω_0 is equal to 1 an space is flat (with zero curvature).

Cosmological Parameters and Dark Energy: Observations of tem perature variations in the cosmic microwave background indicat that the universe is flat or nearly so, with a combined averag mass density equal to the critical density. Observations of galax clusters suggest that the average density of matter in the univers is about 0.24 of the critical density. The remaining contribution t the average density is called dark energy. Therefore, about 0.76, c 76%, of the total energy content of the universe consists of som unknown entity.

- Measurements of Type Ia supernovae in distant galaxies sho that the expansion of the universe is speeding up. This may be du to the presence of dark energy in the form of a cosmological co stant, which provides a pressure that pushes the universe outwar

Cosmological Parameters and Primordial Sound Waves: Temperatu variations in the cosmic background radiation are a record of sour waves in the early universe. Studying the character of these sour waves helps to determine that the universe is flat and other fund mental properties of the universe.

QUESTIONS

Review Questions

1. Why did Isaac Newton conclude that the universe w static? Was he correct?
2. What is Olbers's paradox? How can it be resolved?
3. What is a cosmological constant? Why did Einstein intr duce it into cosmology?
4. TUTORIAL 25-1 What does it mean when astronomers say that we live in an expanding universe? What is actually expanding?
5. Describe how the expansion of the universe explains Hubble's law.
6. Would it be correct to say that due to the expansion of tl universe, Earth is larger today than it was 4.56 billion yea ago? Why or why not?
7. Using a diagram, explain why the expansion of the univer as seen from a distant galaxy would look the same as see from our Galaxy.
8. How does modern cosmology preclude the possibility of e ther a center or an edge to the known universe?
9. Explain the difference between a Doppler shift and a cosm logical redshift.
10. Explain how redshift can be used as a measure of lookbac time. In what ways is it superior to time measured in years
11. By what factor has the universe expanded since $z = 1$? Expla your reasoning.