22

Dark Matter, Dark Energy, and the Fate of the Universe

LEARNING GOALS

22.1 Unseen Influences in the Cosmos
- What do we mean by dark matter and dark energy?

22.2 Evidence for Dark Matter
- What is the evidence for dark matter in galaxies?
- What is the evidence for dark matter in clusters of galaxies?
- Does dark matter really exist?
- What might dark matter be made of?

22.3 Structure Formation
- What is the role of dark matter in galaxy formation?
- What are the largest structures in the universe?

22.4 The Fate of the Universe
- Will the universe continue expanding forever?
- Is the expansion of the universe accelerating?

It is difficult beyond description to conceive that space can have no end; but it is more difficult to conceive an end. It is difficult beyond the power of man to conceive an eternal duration of what we call time; but it is more impossible to conceive a time when there shall be no time.

Thomas Paine, *The Age of Reason (1796)*

In prior chapters, we explored current understanding of the evolution of galaxies in an expanding universe. However, we left at least two crucial questions unaddressed: First, what is the source of the gravity that causes galaxies to form and holds them together? Second, what will happen to the expansion of the universe in the future? Both questions would be interesting in their own right, but they've taken on even greater importance because our attempts to answer them have led us to two of the greatest mysteries in science.

If we are interpreting the data correctly, then the dominant source of gravity in the universe is an unidentified type of mass, known as *dark matter*, that is completely invisible to our eyes and telescopes. The gravity of dark matter must therefore be the "glue" that holds galaxies like our own together. Moreover, the very fate of the universe seems to hinge on the total amount of dark matter and on the existence of an even more mysterious force or energy—often called *dark energy*—that may counteract the effects of gravity on large scales.

In this chapter, we will explore the evidence for dark matter and dark energy and discuss why their natures remain so mysterious. We'll also investigate how dark matter determines the current structure of the universe and the implications of dark energy for the fate of the universe, if dark matter and dark energy indeed prove to be real. Whatever the ultimate answers turn out to be, the quest to resolve these mysteries offers an outstanding opportunity to observe how science progresses. Keep an eye on the science section of your daily newspaper to see how the story unfolds.

22.1 Unseen Influences in the Cosmos

What is the universe made of? Ask an astronomer this seemingly simple question, and you might see a professional scientist blush with embarrassment. Based on all the available evidence today, the answer to this simple question is "We do not know."

It might seem incredible that we still do not know the composition of most of the universe, but you might also wonder why we should be so clueless. After all, astronomers can measure the chemical composition of distant stars and galaxies from their spectra, so we know that stars and gas clouds are made almost entirely of hydrogen and helium, with small amounts of heavier elements mixed in. But notice the key words "chemical composition." When we say these words, we are talking about the composition of material built from atoms of elements such as hydrogen, helium, carbon, and iron. While it is true that all familiar objects—including people, planets, and stars—are built from atoms, the same may not be true of the universe as a whole.

In fact, we now have good reason to think that the vast majority of the matter in the universe is *not* composed of atoms. Instead, the universe may consist largely of a mysterious form of mass known as *dark matter* and a mysterious form of energy known as *dark energy*. As we'll discuss in Chapter 23, some recent observations tell us the precise percentages of the universe that consist of dark energy, dark matter, and ordinary atoms, if we're interpreting these observations properly. Nevertheless, the actual nature of dark matter and dark energy remains completely unknown.

• What do we mean by dark matter and dark energy?

It's easy to talk about dark matter and dark energy, but what do these terms really mean? They are nothing more than names given to unseen influences in the cosmos. In both cases we have been led to think that there is something out there, even though we cannot identify it, because we have observed phenomena that otherwise do not make sense.

We might naively think that the major source of gravity that holds galaxies together is the same gas and dust that make up their stars. However, decades of observations suggest otherwise: By carefully observing gravitational effects on matter that we can see, such as stars or glowing clouds of gas, we've learned that there must be far more matter than meets the eye. Because this matter appears to give off little or no light, we call it **dark matter.** Thus, dark matter is simply a name we give to whatever unseen influence is causing the observed gravitational effects. We've already discussed dark matter briefly in Chapters 1 and 19, noting that studies of the Milky Way's rotation suggest that most of our galaxy's mass is distributed throughout its halo while most of the galaxy's light comes from stars and gas clouds in the thin galactic disk (see Figure 1.15).

We infer the existence of the second unseen influence from careful studies of the expansion of the universe. From the time that Hubble first discovered the expansion, it was generally assumed that gravity must slow the expansion with time. In just the past few years, however, mounting evidence has suggested that the expansion of the universe is actually accelerating. If so, some mysterious type of force or energy must be able to counteract the effects of gravity on very large scales.

Dark energy is the most common name given to whatever it is that may be causing the expansion to accelerate, but it is not the only name; you may occasionally hear the same unseen influence attributed to *quintessence* or to a *cosmological constant*. The term *dark energy* has become popular because it echoes the term *dark matter*, but there's nothing unusually "dark" about it—after all, we don't expect to see light from the mere presence of a force or energy field. Thus, despite the similarity in their names, dark matter and dark energy are thought to exist for completely different reasons.

Astronomers are generally more comfortable with the notion that dark matter exists than with the notion that dark energy exists. Scientific confidence in dark matter has been building for decades and is now at the point where dark matter seems almost indispensable to explaining the current structure of the universe. That is why we will devote most of this chapter to a discussion of dark matter and its presumed role as the dominant source of gravity in our universe—there is simply a lot more we can say about it. We will therefore save discussion of dark energy for the end of the chapter, where we will present the evidence that it also exists and that its nature will determine the fate of the universe.

Before we continue, it's important to think about dark matter and dark energy in the context of science. Upon first hearing of these ideas, you might be tempted to think that astronomers have "gone medieval," arguing about unseen influences in the same way that scholars in medieval times supposedly argued about the number of angels that could dance on the head of a pin. However, strange as the ideas of dark matter and dark energy may seem, they have emerged from careful scientific study conducted in accordance with the hallmarks of science that we discussed in Chapter 3 (see Figure 3.26). Dark matter and dark energy were each proposed to exist because they seemed the simplest ways to explain observed motions in the universe. They've each gained credibility because models of the universe that assume their existence make testable predictions and, at least so far, further observations have borne out some of those predictions. Thus, even if we someday conclude that we were wrong to infer the existence of dark matter or dark energy, we will still need alternative explanations for the observations made to date. One way or the other, what we learn as we explore the mysteries of these unseen influences will forever change our view of the universe.

Detecting Dark Matter in a Spiral Galaxy Tutorial, Lessons 1–3

22.2 Evidence for Dark Matter

We are now ready to begin investigating dark matter in greater detail. In this section, we'll examine the evidence for the existence of dark matter and what the evidence indicates about the nature of dark matter.

• What is the evidence for dark matter in galaxies?

Let's begin our discussion of the evidence for dark matter by examining the case for dark matter in our own Milky Way Galaxy. We'll then proceed to other galaxies and clusters of galaxies.

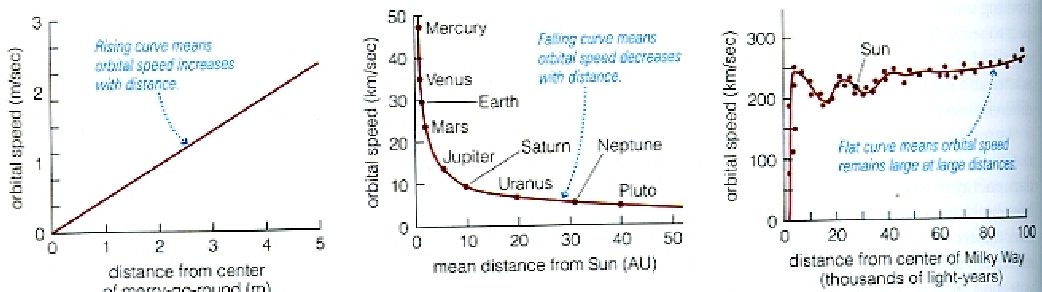
Distribution of Mass in the Milky Way In Chapter 19 we saw how the Sun's motion around the galaxy reveals the total amount of mass within its orbit. Similarly, we can use the orbital motion of any other star to measure the mass of the Milky Way within that star's orbit. In principle, we could determine the complete distribution of mass in the Milky Way by doing the same thing with the orbits of stars at every different distance from the galactic center.

In practice, interstellar dust obscures our view of disk stars more than a few thousand light-years away from us, making it very difficult to measure stellar velocities. However, radio waves penetrate this dust, and clouds of atomic hydrogen gas emit a spectral line at the radio wavelength of 21 centimeters [Section 19.2]. Measuring the Doppler shift of this 21-centimeter line tells us a cloud's velocity toward or away from us. With the help of a little geometry, we can then determine the cloud's orbital velocity.

A diagram called a **rotation curve**, which plots the *rotational velocity* of stars or gas clouds against their distance from the center of the galaxy, summarizes the results of these orbital velocity measurements. As a simple example of the concept, let's construct a rotation curve for a merry-go-round. Every object on a merry-go-round goes around the center with the same rotational period, but objects farther from the center move in larger circles. Thus, objects farther from the center move at faster speeds, and the rotation curve for a merry-go-round is a straight line that rises steadily outward (Figure 22.1a).

In contrast, the rotation curve for our solar system drops off with distance from the Sun, because inner planets orbit at faster speeds than outer planets (Figure 22.1b). This drop-off in speed with distance occurs because virtually all the mass of the solar system is concentrated in the Sun. The gravitational force holding a planet in its orbit decreases with distance from the Sun, and a smaller force means a lower orbital speed. The rotation curve of any astronomical system whose mass is concentrated toward the center must drop similarly.

Figure 22.1c shows the rotation curve for the Milky Way Galaxy. Each individual dot represents the distance from the galactic center and the orbital speed of a particular star or gas cloud. The curve running through the dots represents a "best fit" to the data. Notice that the orbital velocities remain approximately constant beyond the inner few thousand light-years, making the rotation curve look flat. This behavior contrasts sharply with the steeply declining rotation curve of the solar system. Thus, unlike the case for the solar system, most of the mass of the Milky Way must *not* be concentrated at its center. Instead, the orbits of progressively more distant gas clouds must encircle more and more mass. The Sun's orbit encompasses about 100 billion solar masses, but a circle twice as large surrounds twice as much mass, and a larger circle surrounds even more mass. Because of



a A rotation curve for a merry-go-round.

b The rotation curve for the planets in our solar system.

c The rotation curve for the Milky Way Galaxy. Dots represent stars or gas clouds whose rotational speeds have been measured.

Figure 22.1 Interactive Figure Rotation curves show how the orbital speed of a system depends on distance from its center. The solar system's rotation curve declines with radius because its mass is concentrated at the center. The Milky Way's rotation curve is flat, indicating that the Milky Way's mass extends well beyond the Sun's orbit.

the difficulty of finding clouds to measure on the outskirts of the galaxy, we have not yet found the "edge" of this mass distribution.

The flatness of the Milky Way's rotation curve therefore implies that most of our galaxy's mass lies well beyond our Sun, tens of thousands of light-years from the galactic center. A more detailed analysis suggests that most of this mass is located in the spherical halo that surrounds the disk of our galaxy, and that the total amount of this mass might be *10 times* the total mass of all the stars in the disk. Because we have detected very little radiation coming from this enormous amount of mass, it qualifies as dark matter. Thus, if we are interpreting the evidence correctly, the luminous part of the Milky Way's disk must be rather like the tip of an iceberg, marking only the center of a much larger clump of mass (Figure 22.2).

MATHEMATICAL INSIGHT 22.1 Mass-To-Light Ratio

We define an object's mass-to-light ratio as its total mass in units of *solar masses* divided by its total *visible* luminosity in units of *solar luminosities*. Thus, by definition, the mass-to-light ratio of the Sun is:

$$\frac{M}{L} \text{ for Sun} = \frac{1\ M_{Sun}}{1\ L_{Sun}} = 1\ \frac{M_{Sun}}{L_{Sun}}$$

We read this answer with its units as "1 solar mass per solar luminosity." Note that we use M/L as an abbreviation for the mass-to-light ratio in equations, and we always write the mass and luminosity in solar units.

The following examples should clarify the idea of the mass-to-light ratio and show what it can tell us about the existence of dark matter.

Example 1: What is the mass-to-light ratio of a 1 M_{Sun} red giant with luminosity 100 L_{Sun}? What does the answer tell us about how mass-to-light ratio depends on stellar type?

Solution:

Step 1 Understand: Finding a mass-to-light ratio simply requires knowing an object's total mass in solar masses and its total luminosity in solar luminosities. We are told that the object is a star of 1 solar mass with a luminosity 100 times that of the Sun, so we have all the information we need.

Step 2 Solve: We divide the star's mass by its luminosity, both in solar units:

$$\frac{M}{L} = \frac{1\ M_{Sun}}{100\ L_{Sun}} = 0.01\ \frac{M_{Sun}}{L_{Sun}}$$

Step 3 Explain: The red giant has a mass-to-light ratio of 0.01 solar mass per solar luminosity. The ratio is *less* than 1 because a red giant puts out *more* light per unit mass than the Sun. Massive stars also put out more light per unit mass than the Sun, because main-sequence luminosities rise much faster than main-sequence masses [Section 15.2]. Thus, in general, stars *more luminous* than the Sun have mass-to-light ratios *less* than 1 solar mass per solar luminosity. Conversely, stars that are *less luminous* than the Sun generally have mass-to-light ratios *greater* than 1 solar mass per solar luminosity.

Example 2: The Sun's orbit around the Milky Way tells us that the part of the galaxy within the Sun's orbit contains about 90 billion (9×10^{10}) solar masses of material. Observations tell us that the total luminosity of stars within that same region is about 15 billion (1.5×10^{10}) solar luminosities. What is the mass-to-light ratio of the matter in our galaxy within the Sun's orbit? What does this imply?

THINK ABOUT IT

Suppose we made a rotation curve for the moons orbiting Jupiter. Would it rise, increase, or stay flat with increasing distance of Jupiter?

Dark Matter in Other Spiral Galaxies Other galaxies also seem to contain vast quantities of dark matter. We can determine the amount of dark matter in a galaxy by comparing the galaxy's mass to its luminosity. (More formally, astronomers calculate the galaxy's *mass-to-light ratio*; see Mathematical Insight 22.1.) The procedure is fairly simple in principle. First, we use the galaxy's luminosity to estimate the amount of mass that the galaxy contains in the form of stars. Next, we determine the galaxy's total mass by applying the law of gravity to observations of the orbital velocities of stars and gas clouds. If this total mass is larger than the mass that we can attribute to stars, then we infer that the excess mass must be dark matter.

Measuring a galaxy's luminosity is relatively easy, as long as we can determine its distance with one of the techniques discussed in Chapter 20. We simply point a telescope at the galaxy in question, measure its apparent brightness, and calculate its luminosity from its distance and the inverse square law of light [Section 15.1]. Measuring the galaxy's total mass requires measuring orbital speeds of stars or gas clouds as far from the galaxy's center as possible. Atomic hydrogen gas clouds can be found in spiral galaxies at greater distances from the center than stars, so most of our data come from radio observations of the 21-centimeter line from these clouds. We use Doppler shifts of the 21-centimeter line to determine how fast a cloud is moving toward us or away from us (Figure 22.3). We then combine observations for clouds at varying orbital distances to construct the galaxy's rotation curve.

The rotation curves of most spiral galaxies turn out to be remarkably flat as far out as we can see (Figure 22.4). Just as in the Milky Way, these flat rotation curves imply that a great deal of matter lies far out in the halos of these other

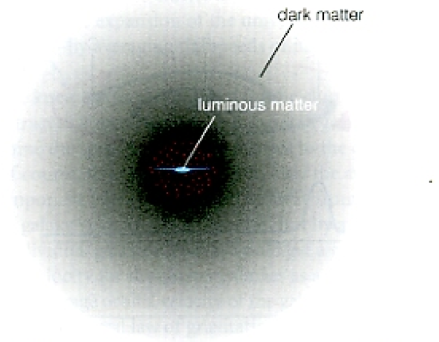


Figure 22.2 The dark matter associated with a spiral galaxy like the Milky Way occupies a much larger volume than the galaxy's luminous matter. The radius of this dark-matter halo may be 10 times as large as the galaxy's halo of stars.

Solution:

Step 1 Understand: We are asked to find the mass-to-light ratio for the region of our galaxy within the Sun's orbit. We are given both the mass and luminosity of this region in solar units, so we have all the information we need.

Step 2 Solve: We divide the region's mass by its luminosity, both in solar units:

$$\frac{M}{L} = \frac{9 \times 10^{10}\, M_{Sun}}{1.5 \times 10^{10}\, L_{Sun}} = 6\,\frac{M_{Sun}}{L_{Sun}}$$

Step 3 Explain: The mass-to-light ratio of the matter within the Sun's orbit is about six solar masses per solar luminosity. Because this mass-to-light ratio is *greater* than the Sun's ratio of 1 solar mass per solar luminosity, it tells us that most matter in this region is *dimmer* per unit mass than our Sun. This is not surprising, because we know that most stars are smaller and dimmer than our Sun.

Example 3: The rotation curve of a nearby spiral galaxy shows that it contains 5×10^{11} solar masses within a radius of 150,000 light-years of its center. Its apparent brightness and distance tell us that its total luminosity is 1.5×10^{10} solar luminosities. What is its mass-to-light ratio? What does this imply?

Solution:

Step 1 Understand: In this case, we are given the galaxy's full mass (out to the large distance of 150,000 light-years from its center), determined from its rotation curve and its total luminosity. Thus, we again have all the information we need to calculate the mass-to-light ratio.

Step 2 Solve: We divide the galaxy's mass by its luminosity, both in solar units:

$$\frac{M}{L} = \frac{5 \times 10^{11}\, M_{Sun}}{1.5 \times 10^{10}\, L_{Sun}} = 33\,\frac{M_{Sun}}{L_{Sun}}$$

Step 3 Explain: The mass-to-light ratio of this galaxy is about 33 solar masses per solar luminosity, which is more than five times as large as the mass-to-light ratio for the Milky Way Galaxy within the Sun's orbit. This mass-to-light ratio tells us that on average, the mass in this galaxy is much less luminous than the mass found in the inner regions of the Milky Way. We were able to explain a mass-to-light ratio of six solar masses per solar luminosity as a simple consequence of the fact that most stars are dimmer than the Sun. However, this far greater ratio of 33 solar masses per solar luminosity is not so easily explained by stars; instead, we conclude that the large mass-to-light ratio is telling us that the galaxy must contain a lot of mass that emits little or no light; that is, it contains dark matter.

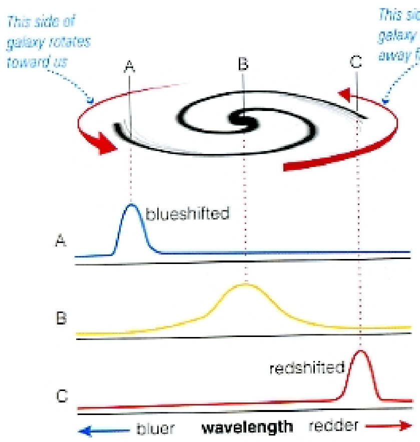


Figure 22.3 Measuring the rotation of a spiral galaxy with the 21-centimeter line of atomic hydrogen. Blueshifted lines on the left side of the disk show how fast that side is rotating toward us. Redshifted lines on the right side show how fast that side is rotating away from us.

spiral galaxies. A detailed analysis tells us that these other spiral galaxies also have at least 10 times as much mass in dark matter as they do in stars. In other words, typical spiral galaxies are made of 90% or more dark matter, and 10% or less matter in stars.

Dark Matter in Elliptical Galaxies We must use a different technique to weigh elliptical galaxies, because most of them contain very little atomic hydrogen gas and hence do not produce detectable 21-centimeter radiation. We generally weigh the inner parts of elliptical galaxies by observing the motions of the stars themselves.

The motions of stars in an elliptical galaxy are disorganized, so we cannot assemble their velocities into a sensible rotation curve. Nevertheless, the velocity of each individual star still depends on the mass inside the star's orbit. At any particular distance from an elliptical galaxy's center, some stars are moving toward us and some are moving away

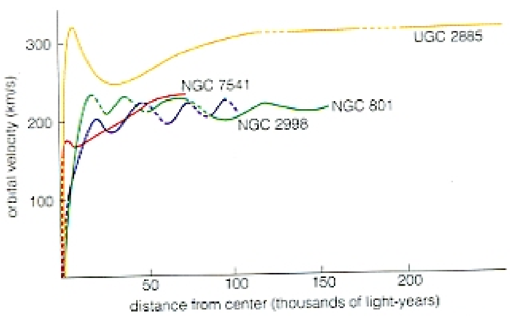


Figure 22.4 Actual rotation curves of four spiral galaxies. They are all nearly flat over a wide range of distances from the center, indicating that dark matter is common in spiral galaxies.

from us. As a result, every star has a slightly different Doppler shift. When we look at spectral lines from the galaxy as a whole, we see the combined effect of all these Doppler shifts. Together, they change the spectral line from a nice narrow line at a particular wavelength to a *broadened* line spanning a range of wavelengths (Figure 22.5). The greater the broadening of the spectral line, the faster the stars must be moving.

When we compare spectral lines from different regions of an elliptical galaxy, we find that the speeds of the stars remain fairly constant as we look farther from the galaxy's center. Thus, just as in spirals, most of the matter in elliptical galaxies must lie beyond the distance where the light trails off and hence must be dark matter. The evidence for dark matter becomes even more convincing in cases in which we can measure the speeds of globular star clusters orbiting at large distances from the center of an elliptical galaxy. These measurements suggest that elliptical galaxies, like spirals, contain far more matter than we can see in the form of stars.

• What is the evidence for dark matter in clusters of galaxies?

The evidence we have discussed so far indicates that stars make up only about 10% of a galaxy's mass—the remaining mass consists of dark matter. Observations of galaxy clusters suggest that the total proportion of dark matter is even greater. The mass of dark matter in clusters appears to be as much as 50 times the mass in stars.

The evidence for dark matter in clusters comes from three different ways of measuring cluster masses: measuring the speeds of galaxies orbiting the center of the cluster, studying the X-ray emission from hot gas between the cluster galaxies, and observing how the clusters bend light as

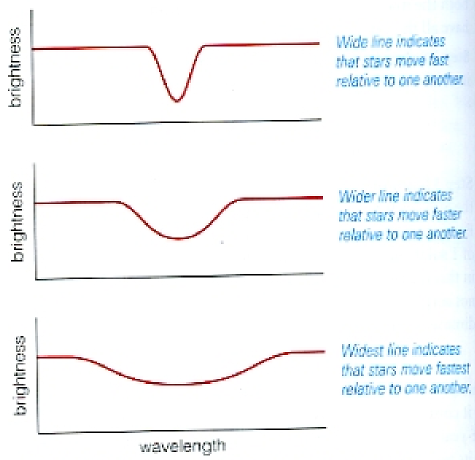


Figure 22.5 The broadening of absorption lines in an elliptical galaxy's spectrum tells us how fast its stars move relative to one another.

gravitational lenses. Let's investigate each of these techniques more closely.

Orbits of Galaxies in Clusters The problem of dark matter in astronomy is not particularly new. In the 1930s, astronomer Fritz Zwicky was already arguing that clusters of galaxies held enormous amounts of this mysterious stuff (Figure 22.6). Few of his colleagues paid attention, but later observations supported Zwicky's claims.

Zwicky was one of the first astronomers to think of galaxy clusters as huge swarms of galaxies bound together by gravity. It seemed natural to him that galaxies clumped closely together in space should all be orbiting one another, just like the stars in a star cluster. He therefore assumed that he could measure cluster masses by observing galaxy motions and applying Newton's laws of motion and gravitation.

Armed with a spectrograph, Zwicky measured the redshifts of the galaxies in a particular cluster and used these redshifts to calculate the speeds at which the individual galaxies are moving away from us. He determined the recession speed of the cluster as a whole—that is, the speed at which the expansion of the universe carries it away from us—by averaging the speeds of its individual galaxies.

Once he knew the recession speed for the cluster, Zwicky could subtract this speed from each individual galaxy's speed to determine the speeds of galaxies relative to the cluster center. Of course, this method told him only the average *radial* component (the speed toward or away from us) of the actual galaxy velocities [Section 5.5], but by averaging enough individual galaxies, Zwicky could get a good average orbital velocity for the cluster galaxies as a whole. Once he knew the average orbital velocity of the galaxies, he could use Newton's universal law of gravitation to estimate the cluster's mass (see Mathematical Insight 22.2). Finally, he compared the cluster's mass to its luminosity.

To his surprise, Zwicky found that clusters of galaxies have much greater masses than their luminosities would suggest. That is, when he estimated the total mass of stars necessary to account for the overall luminosity of a cluster, he found that it was far less than the mass he measured

MATHEMATICAL INSIGHT 22.2 Cluster Masses from Galaxy Orbits

The first method described in the text for measuring the masses of galaxy clusters relies on the *orbital velocity law* introduced in Mathematical Insight 19.1:

$$M_r = \frac{r \times v^2}{G}$$

where M_r is the total mass contained *within* a distance r of a galaxy's center, v is the average velocity of objects orbiting the center of the galaxy, and G is the gravitational constant ($G = 6.67 \times 10^{-11}\ \text{m}^3/(\text{kg} \times \text{s}^2)$). Recall that this law is derived from Newton's version of Kepler's third law, which in turn is derived from Newton's universal law of gravitation. Thus, the orbital velocity law is simply a convenient way of using the law of gravitation to calculate a galaxy's mass from the speeds of orbiting objects.

This law also applies to galaxy clusters (and other objects) if we simply consider r as the distance from the center of the cluster (or other object) rather than from the center of an individual galaxy. However, it is exact only for galaxies on circular orbits.

Example: A galaxy cluster has a radius of 6.2 million light-years, and Doppler shift measurements show that its galaxies orbit the center of the cluster with an average speed of approximately 1,350 km/s. Find the cluster's mass.

Solution:

Step 1 Understand: We can find the cluster's mass from the orbital velocity law above because we are given both the cluster radius (r in the formula) and the average orbital speed of the galaxies (v in the formula). However, we cannot directly use the given values because their units are inconsistent: The radius is given in light-years but the speed is given in kilometers per second. Moreover, we are given the gravitational constant G in units that use meters. Thus, before we can solve the problem, we'll need to convert the radius into meters and the speed into meters per second.

Step 2 Solve: We first need to perform the unit conversions on the given values; then we can plug the results into the orbital velocity law. You should confirm for yourself that the radius (r) of 6.2 million light-years is equivalent to 5.9×10^{22} meters and that the speed (v) of 1,350 km/s is equivalent to 1.35×10^6 m/s. Using these values, we find:

$$\begin{aligned} M_r &= \frac{r \times v^2}{G} \\ &= \frac{(5.9 \times 10^{22}\ \text{m}) \times (1.35 \times 10^6\ \text{m/s})^2}{6.67 \times 10^{-11}\ \frac{\text{m}^3}{\text{kg} \times \text{s}^2}} \\ &= 1.6 \times 10^{45}\ \text{kg} \end{aligned}$$

Step 3 Explain: We have found that the mass of the cluster is 6.7×10^{44} kilograms. However, it's difficult to interpret such a large mass expressed in kilograms, so we need to convert it to a more appropriate unit. In this case, where we are dealing with the mass of a galaxy, the most appropriate unit is solar masses. Looking back at Chapter 14 or in Appendix E, you'll find that the Sun's mass is 2.0×10^{30} kilograms. Thus, the cluster mass in units of solar masses is:

$$M_r = 1.6 \times 10^{45}\ \text{kg} \times \frac{1\ M_{Sun}}{2 \times 10^{30}\ \text{kg}} \approx 8.0 \times 10^{14}\ M_{Sun}$$

The cluster mass is about 8.0×10^{14}, or 800 trillion, solar masses. If you recall that the total mass of the Milky Way (including dark matter) is somewhere near 1 trillion solar masses, you'll see that the cluster contains the equivalent mass of about 800 galaxies as large as the Milky Way.

by studying galaxy speeds. He concluded that most of the matter within these clusters must not be in the form of stars and instead must be almost entirely dark. Many astronomers disregarded Zwicky's result, believing that he must have done something wrong to arrive at such a strange answer. Today, far more sophisticated measurements of galaxy orbits in clusters confirm Zwicky's original finding.

THINK ABOUT IT

What would happen to a cluster of galaxies if you instantly removed all the dark matter without changing the velocities of the galaxies?

Hot Gas in Clusters A second method for measuring the mass of a cluster of galaxies relies on observing X rays from the hot gas that fills the space between the galaxies in the cluster (Figure 22.7). This gas (sometimes called the *intracluster medium*) is so hot that it emits primarily X rays and therefore went undetected until the 1960s, when X-ray telescopes were finally launched above Earth's atmosphere. The temperature of this gas is tens of millions of degrees in many clusters and can exceed 100 million degrees in the largest clusters. This hot gas can also contain a great deal of mass. Large clusters have up to seven times as much mass in the form of X-ray-emitting gas than they do in the form of stars.

The hot gas can tell us about dark matter because its temperature depends on the total mass of the cluster. The gas in most clusters is nearly in a state of *gravitational equilibrium*—that is, the outward gas pressure balances gravity's inward pull [Section 14.1]. In this state of balance, the average kinetic energies of the gas particles are determined primarily by the strength of gravity and hence by the amount of mass within the cluster. Because the temperature of a gas reflects the average kinetic energies of its particles, the gas temperatures we measure with X-ray telescopes tell us the average speeds of the X-ray-emitting particles (see Mathematical Insight 22.3). We can then use these particle speeds to determine the cluster's total mass.

The results obtained with this method agree well with the results found by studying the orbital motions of the cluster's galaxies. Even after we account for the mass of the

Figure 22.6 Fritz Zwicky, discoverer of dark matter in clusters of galaxies. Zwicky had an eccentric personality, but some of his ideas that seemed strange in the 1930s proved correct many decades later.

SPECIAL TOPIC Pioneers of Science

Scientists always take a risk when they publish what they think are groundbreaking results. If their results turn out to be in error, their reputations may suffer. When it came to dark matter, the pioneers in its discovery risked their entire careers. A case in point is Fritz Zwicky, and his proclamations in the 1930s about dark matter in clusters of galaxies. Most of his colleagues considered him an eccentric who leapt to premature conclusions.

Another pioneer in the discovery of dark matter was Vera Rubin, an astronomer at the Carnegie Institution. Working in the 1960s, she became the first woman to observe under her own name at California's Palomar Observatory, then the largest telescope in the world. (Another woman, Margaret Burbidge, was permitted to observe at Palomar earlier but was required to apply for time under the name of her husband, also an astronomer.) Rubin first saw the gravitational signature of dark matter in spectra that she recorded of stars in the Andromeda Galaxy. She noticed that stars in the outskirts of Andromeda moved at surprisingly high speeds, suggesting a stronger gravitational attraction than the mass of the galaxy's stars alone could explain. In other words, she found that the rotation curve for Andromeda is relatively flat to great distances from the center, just as we now know is also the case for the Milky Way.

Working with a colleague, Kent Ford, Rubin constructed rotation curves for the hydrogen gas in many other spiral galaxies (by studying Doppler shifts in the spectra of hydrogen gas) and discovered that flat rotation curves are common. Although Rubin and Ford did not immediately recognize the significance of the results, they were soon arguing that the universe must contain substantial quantities of dark matter.

For a while, many other astronomers had trouble believing the results. Some astronomers suspected that the bright galaxies studied by Rubin and Ford were unusual for some reason. So Rubin and Ford went back to work, obtaining rotation curves for fainter galaxies. They found flat rotation curves—a signature of dark matter—even in these galaxies. By the 1980s, the evidence that Rubin, Ford, and other astronomers measuring rotation curves had compiled was so overwhelming that even the critics came around. Either the theory of gravity was wrong, or the astronomers measuring rotation curves had discovered dark matter in spiral galaxies.

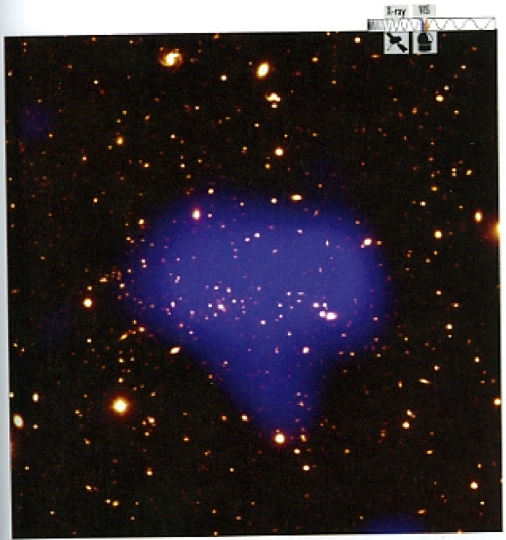


Figure 22.7 A distant cluster of galaxies in both visible light and X-ray light. The visible-light photo shows the individual galaxies as whitish blobs. The blue overlay represents X-ray emission from extremely hot gas (around 100 million Kelvin) in the cluster. Evidence for dark matter comes both from the observed motions of the visible galaxies and from the temperature of the hot gas. (The photo shows a region about 8 million light-years across.)

hot gas, we find that the amount of dark matter in clusters of galaxies is up to 50 times that of the combined mass of the stars in the cluster's galaxies. In other words, the gravity of dark matter seems to be binding the galaxies of a cluster together in much the same way that gravity helps bind individual galaxies together.

Gravitational Lensing Until very recently, astronomers relied exclusively on methods based on Newton's laws to measure galaxy and cluster masses. These laws keep telling us that the universe holds far more matter than we can see. Can we trust these laws? One way to check is to measure masses in a different way. Today, astronomers have another tool for measuring masses: *gravitational lensing.*

Gravitational lensing occurs because masses distort spacetime—the "fabric" of the universe [Section S3.3]. Massive objects can therefore act as **gravitational lenses** that bend light beams passing nearby. This prediction of Einstein's general theory of relativity was first verified in 1919 during an eclipse of the Sun [Section S3.4]. Because the light-bending angle of a gravitational lens depends on the mass of the object doing the bending, we can measure the masses of objects by observing how strongly they distort light paths.

Figure 22.8 shows a striking example of how a cluster of galaxies can act as a gravitational lens. Many of the yellow elliptical galaxies concentrated toward the center of

MATHEMATICAL INSIGHT 22.3 Cluster Masses from Gas Temperature

To find a cluster's mass from the temperature of its hot, X-ray-emitting gas, we need to know how the gas temperature is related to the speeds of individual gas particles. Although we will not present a derivation here, the following formula tells us the approximate speed at which hydrogen nuclei move around a cluster if its hot gas has a temperature T:

$$v_H = 140\,\tfrac{\text{m}}{\text{s}} \times \sqrt{T}$$

where v_H is the average orbital speed of the hydrogen nuclei and T is the temperature in Kelvin. We can use this formula for the hot gas in galaxy clusters because most of the gas is composed of hydrogen. Once we find the speeds of the hydrogen nuclei, we can use them in the orbital velocity law to find the cluster mass.

Example: Consider the galaxy cluster described in the Example in Mathematical Insight 22.2, with a radius of 6.2 million light-years. Suppose the cluster is filled with hot gas that has a temperature of 9×10^7 K. Use this temperature to find the cluster's mass.

Solution:

Step 1 Understand: We are given a gas temperature and asked to find a cluster mass. From Mathematical Insight 22.2, we know that we can use the orbital velocity law to find the cluster mass if we know the cluster's radius (r) and the average velocity (v) of orbiting particles. We are given the cluster's radius of 6.2 million light-years, and we already found that this is equivalent to 5.9×10^{22} meters. We can use the formula given above to find the average orbital speed of hydrogen nuclei, which we can use as the velocity (v) in the orbital velocity law.

Step 2 Solve: First, we find the average orbital speed of the hydrogen nuclei from the given temperature of 9×10^7 K:

$$\begin{aligned} v_H &= 140\,\tfrac{\text{m}}{\text{s}} \times \sqrt{T} \\ &= 140\,\tfrac{\text{m}}{\text{s}} \times \sqrt{9 \times 10^7} \\ &= 1.3 \times 10^6\,\tfrac{\text{m}}{\text{s}} \end{aligned}$$

Now we use this value as v in the orbital velocity law, along with the cluster radius $r = 4.5 \times 10^{22}$ meters. We find that the cluster mass is:

$$\begin{aligned} M_r &= \frac{r \times v^2}{G} \\ &= \frac{(5.9 \times 10^{22}\text{ m}) \times (1.3 \times 10^6\text{ m/s})^2}{6.67 \times 10^{-11}\,\frac{\text{m}^3}{\text{kg} \times \text{s}^2}} \\ &\approx 1.5 \times 10^{45}\text{ kg} \end{aligned}$$

Step 3 Explain: We have found that the mass of the cluster is 1.5×10^{45} kilograms. You should confirm for yourself that this is equivalent to about 750 trillion solar masses. Note that this is just slightly lower than the 800 trillion solar masses that we found in Mathematical Insight 22.2 from the galaxy speeds, showing that the two methods of estimating mass agree well in this example.

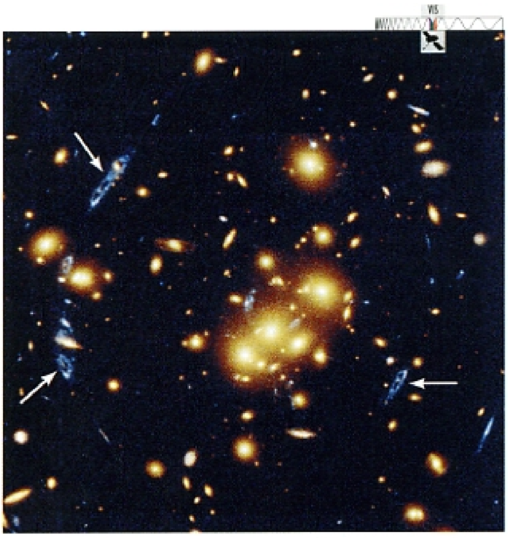


Figure 22.8 Interactive Photo This Hubble Space Telescope photo shows a galaxy cluster acting as a gravitational lens. The yellow elliptical galaxies are cluster members. The many small blue ovals (such as those indicated by the arrows) are multiple images of a single galaxy that lies almost directly behind the cluster's center. (The picture shows a region about 1.4 million light-years across.)

the picture belong to the cluster, but at least one of the galaxies pictured does not. At several positions on various sides of the central clump of yellow galaxies, you will notice multiple images of the same blue galaxy. Each one of these images, whose sizes differ, looks like a distorted oval with an off-center smudge.

The blue galaxy seen in these multiple images lies almost directly behind the center of the cluster, at a much greater distance. We see multiple images of this single galaxy because photons do not follow straight paths as they travel from the galaxy to Earth. Instead, the cluster's gravity bends the photon paths, allowing light from the galaxy to arrive at Earth from a few slightly different directions (Figure 22.9). Each alternative path produces a separate, distorted image of the blue galaxy.

Multiple images of a gravitationally lensed galaxy are rare. They occur only when a distant galaxy lies directly behind the lensing cluster. However, single, distorted images of gravitationally lensed galaxies are quite common. Figure 22.10 shows a typical example. This picture shows numerous normal-looking galaxies and several arc-shaped galaxies. The oddly curved galaxies are not members of the cluster, nor are they really curved. They are normal galaxies lying far beyond the cluster whose images have been distorted by the cluster's gravity.

Careful analyses of the distorted images created by clusters enable us to measure cluster masses without resorting to Newton's laws. Instead, Einstein's general theory of relativity tells us how massive these clusters must be to generate the observed distortions. It is reassuring that cluster masses derived in this way generally agree with those de-

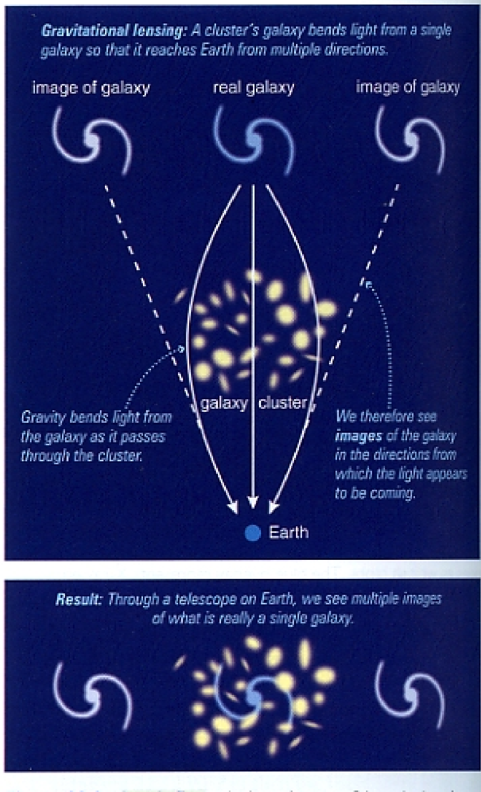


Figure 22.9 Interactive Figure A cluster's powerful gravity bends light paths from background galaxies to Earth. If light can arrive from several different directions, we see multiple images of the same galaxy.

rived from galaxy velocities and X-ray temperatures. The three different methods all indicate that clusters of galaxies hold very substantial amounts of dark matter.

• Does dark matter really exist?

Astronomers have made a strong case for the existence of dark matter, but could they be completely off base? Is it possible that dark matter is a figment of human imagination, and that there's a completely different explanation for the observations we've discussed? Addressing these questions gives us a chance to see how science progresses.

All the evidence for dark matter rests on our understanding of gravity. For individual galaxies, the case for dark matter rests primarily on applying Newton's laws of motion and gravity to observations of the orbital speeds of stars and gas clouds. We've used the same laws to make the case for dark matter in clusters, along with additional evidence based on gravitational lensing predicted by Einstein's general theory of relativity. Thus, it seems that one of the following must be true:

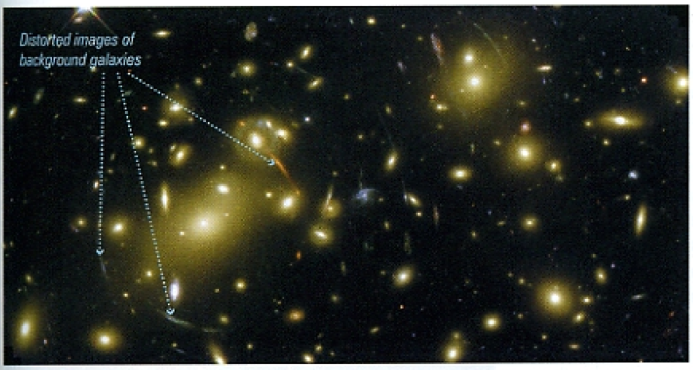


Figure 22.10 Hubble Space Telescope photo of the cluster Abell 2218. The thin, elongated galaxies around the main clump of galaxies on the left side of the picture are the images of background galaxies distorted by the cluster's gravity. By measuring these distortions, astronomers can determine the total amount of mass in the cluster. (The region pictured is about 1.4 million light-years from side to side.)

1. Dark matter really exists, and we are observing the effects of its gravitational attraction.
2. There is something wrong with our understanding of gravity that is causing us to mistakenly infer the existence of dark matter.

We cannot yet rule out the second possibility, but most astronomers consider it very unlikely. Newton's laws of motion and gravity are among the most trustworthy tools in science. We have used them time and again to measure masses of celestial objects from their orbital properties. We found the masses of Earth and the Sun by applying Newton's version of Kepler's third law to objects that orbit them [Section 4.4]. We used this same law to calculate the masses of stars in binary star systems, revealing the general relationships between the masses of stars and their outward appearances. Newton's laws have also told us the masses of things we can't see directly, such as the masses of orbiting neutron stars in X-ray binaries and of black holes in active galactic nuclei. Einstein's general theory of relativity likewise stands on solid ground, having been repeatedly tested and verified to high precision in many observations and experiments. Thus, we have good reason to trust our current understanding of gravity.

Moreover, many scientists have already made valiant efforts to come up with alternate theories of gravity that could account for the observations implying the existence of dark matter in some other way. (After all, there's a Nobel Prize waiting for anyone who can substantiate a new theory of gravity.) So far, no one has succeeded in doing so in a way that can still explain the many other observations accounted for by our current theories of gravity.

In essence, our high level of confidence in our current understanding of gravity gives us equally high confidence that dark matter really exists. Thus, while we should always keep an open mind about the possibility of future changes in our understanding, we will proceed for now under the assumption that dark matter is real. With that assumption in mind, let's turn our attention to the nature of what seems to be the most common form of matter in the universe.

THINK ABOUT IT

Should the fact that we have three different ways of measuring cluster masses give us greater confidence that we really do understand gravity and that dark matter really does exist? Why or why not?

• What might dark matter be made of?

What is all this dark stuff in galaxies and clusters of galaxies? We don't yet know. Nevertheless, we can make at least some educated guesses.

At least some of the dark matter is likely to be *ordinary,* made of protons, neutrons, and electrons. The only unusual thing about dark matter of this kind is that it doesn't emit much detectable radiation. Otherwise, it is made of the same stuff as all the "bright matter" that we can see. However, as we'll discuss shortly, it's also likely that some of the dark matter is *extraordinary,* made of particles that we have yet to discover.

A bit of terminology will be useful. Because the protons and neutrons that make up most of the mass of ordinary matter belong to a category of particles called **baryons**, ordinary matter is sometimes called **baryonic matter.** By extension, extraordinary matter is called **nonbaryonic matter.**

Ordinary Dark Matter Matter need not be extraordinary to be dark. In astronomy, "dark" merely means "not as bright as a normal star and therefore not visible across vast distances of space." Your body is dark matter, because you would be far too dim for our telescopes to detect if you were somehow flung into the halo of our galaxy. Everything you own is dark matter. Earth and the rest of the planets are dark matter as well. In fact, the "failed stars" known as *brown dwarfs* [Section 16.3] and even faint red main-sequence stars of spectral type M [Section 15.2] are too dim for current telescopes to see in the halo and therefore qualify as dark matter. Thus, it's conceivable that trillions of faint red stars, brown dwarfs, and Jupiter-size objects left over from the Milky Way's formation still roam our galaxy's halo, providing much of its mass. These objects are sometimes called

MACHOs, for *massive compact halo objects*, although they are better thought of as dim, starlike (or planetlike) objects.

MACHOs such as brown dwarfs and dim, red stars are too faint for us to see directly, but there are other ways to search for them. One innovative technique takes advantage of gravitational lensing on a much smaller scale than the examples we studied for clusters of galaxies. If trillions of these dim stars and similar objects really roam the halo of the galaxy, every once in a while one of them should drift across our line of sight to a more distant star. When the object lies almost directly between us and the farther star, its gravity will focus more of the star's light directly toward Earth. The distant star will appear much brighter than usual for several days or weeks as the lensing object passes in front of it (Figure 22.11). We cannot see the lensing object itself, but the duration of the lensing event reveals its mass.

Gravitational lensing events such as these are rare, happening to about one star in a million each year. To detect such lensing events, we therefore must monitor huge numbers of stars. Current large-scale monitoring projects now record numerous lensing events annually. These events demonstrate that dim, starlike objects (MACHOs) do indeed populate our galaxy's halo, but not in large enough numbers to account for all the Milky Way's dark matter. Similar measurements rule out the possibility that the dark matter consists of large numbers of black holes formed by the deaths of massive stars.* Something else lurks unseen in the outer reaches of our galaxy.

Extraordinary Dark Matter A more exotic possibility is that most of the dark matter in galaxies and clusters of galaxies is not made of ordinary, baryonic matter at all. Let's begin to explore this possibility by taking another look at those nonbaryonic particles we discussed in Section 14.2: neutrinos. These unusual particles are dark by their very nature, because they have no electrical charge and hence cannot emit electromagnetic radiation of any kind. Moreover, they are never bound together with charged particles in the way that neutrons are bound in atomic nuclei, so their presence cannot be revealed by associated light-emitting particles.

Particles like neutrinos interact with other forms of matter through only two of the four forces: gravity and the *weak force* [Section S4.2]. For this reason, they are said to be *weakly interacting particles*. If you recall that trillions of neutrinos from the Sun are passing through your body at this very moment without doing any damage, you'll see why the name *weakly interacting* fits well.

The dark matter in galaxies cannot be made of neutrinos, because these very-low-mass particles travel through the universe at enormous speeds and can easily escape a galaxy's gravitational pull. (However, neutrinos make up a small amount of the dark matter outside galaxies.) What if other weakly interacting particles exist that are similar to neutrinos but considerably heavier? They too would evade direct detection, but they would move more slowly so that their mutual gravity could hold together a large collection of them. Such hypothetical particles are called **WIMPs**, for *weakly interacting massive particles*. Note that WIMPs are subatomic particles, so the "massive" in their name is relative—they are "massive" only in comparison to lightweight particles like neutrinos. (They are also often called *cold dark matter* to set them apart from the faster-moving neutrinos.) WIMPs could make up most of the mass of a galaxy or cluster of galaxies, but they would be completely invisible in all wavelengths of light. Most astronomers now consider it likely that WIMPs make up the vast majority of dark matter, and hence the majority of all matter in the universe.

It might surprise you that scientists suspect the universe to be filled with particles they haven't yet discovered. However, this hypothesis would also explain why dark matter seems to be distributed throughout spiral galaxy halos rather than concentrated in flattened disks like the visible matter. Recall that galaxies are thought to have formed as gravity

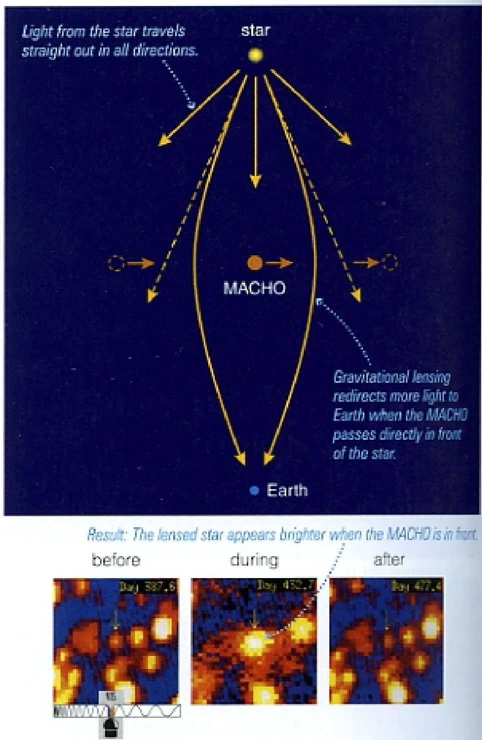


Figure 22.11 When a small, starlike object (MACHO) passes in front of a more distant star, gravitational lensing temporarily makes the star appear brighter. Searches for such events show that our galaxy's halo does indeed contain dim, starlike objects, but that these objects do not constitute the majority of the galaxy's dark matter.

*Lensing observations cannot yet rule out the presence of black holes with masses less than those of stars. Such low-mass black holes could conceivably be left over from the Big Bang, but our best theoretical models of the early universe do not predict a large enough number of them to account for the dark matter.

pulled together matter in regions of slightly enhanced density in the early universe [Section 21.1]. This matter would have consisted mostly of dark matter mixed with some ordinary (hydrogen and helium) gas. The ordinary gas could collapse to form a rotating disk because individual gas particles could lose orbital energy: Collisions among gas particles can convert some of their orbital energy into radiative energy that escapes from the galaxy in the form of photons. In contrast, WIMPs cannot produce photons and they rarely interact and exchange energy with other particles. Thus, as the gas collapsed to form a disk, WIMPs would have remained stuck on orbits far out in the galactic halo—just where most dark matter seems to be located.

By itself, the agreement between the measured distribution of dark matter in galaxies and what we'd expect from dark matter made of WIMPs doesn't prove that extraordinary dark matter exists. However, as we'll discuss in the next chapter, there are additional reasons many astronomers believe that baryons represent only a minority of the universe's mass and hence that WIMPs are the most common form of matter in the universe.

THINK ABOUT IT

What do you think of the idea that much of the universe is made of as-yet-undiscovered particles? Can you think of other instances in the history of science in which the existence of something was predicted before it was discovered?

22.3 Structure Formation

Dark matter remains enigmatic, but every year we are learning more about its role in the universe. Because galaxies and clusters of galaxies seem to contain much more dark matter than luminous matter, dark matter's gravitational pull must be the primary force holding these structures together. Thus, we strongly suspect that the gravitational attraction of dark matter is what pulled galaxies and clusters together in the first place.

• What is the role of dark matter in galaxy formation?

Stars, galaxies, and clusters of galaxies are all *gravitationally bound systems*—their gravity is strong enough to hold them together. In most of the gravitationally bound systems we have discussed so far, gravity has completely overwhelmed the expansion of the universe. That is, while the universe as a whole is expanding, space is *not* expanding within our solar system, our galaxy, or our Local Group of galaxies.

Our best guess at how galaxies formed, outlined in Section 21.2, envisions them growing from slight density enhancements that were present in the very early universe. During the first few million years after the Big Bang, the universe expanded everywhere. Gradually, the stronger gravity in regions of enhanced density pulled in matter until these regions stopped expanding and became protogalactic clouds, even as the universe as a whole continued (and still continues) to expand.

If dark matter is indeed the most common form of mass in galaxies, it must have provided most of the gravitational attraction responsible for creating the protogalactic clouds. The hydrogen and helium gas in the protogalactic clouds collapsed inward and gave birth to stars, while weakly interacting dark matter remained in the outskirts because of its inability to radiate away its orbital energy. According to this model, the luminous matter in each galaxy must still be nestled inside the larger cocoon of dark matter that initiated the galaxy's formation (see Figure 22.2), just as observational evidence seems to suggest.

The formation of galaxy clusters probably echoes the formation of galaxies. Early on, all the galaxies that will eventually constitute a cluster are flying apart with the expansion of the universe, but the gravity of the dark matter associated with the cluster eventually reverses the trajectories of these galaxies. The galaxies ultimately fall back inward and start orbiting each other randomly, like the stars in the halo of our galaxy.

Some clusters of galaxies apparently have not yet finished forming, because their immense gravity is still drawing in new members. For example, the large and relatively nearby Virgo Cluster of galaxies (about 60 million light-years away) appears to be drawing in the Milky Way and other galaxies of the Local Group. The evidence comes from careful study of galaxy speeds. Plugging the Virgo Cluster's distance into Hubble's law tells us the speed at which the Milky Way and the Virgo Cluster should be drifting apart due to the universal expansion [Section 20.2]. However, the measured speed is about 400 km/s slower than the speed we predict from Hubble's law alone. We conclude that this 400 km/s discrepancy (sometimes called a *peculiar velocity*) arises because the Virgo Cluster's gravity is pulling us back against the flow of universal expansion. In other words, while the Milky Way and other galaxies of our Local Group are still moving away from the Virgo Cluster with the expansion of the universe, the rate at which we are separating from the cluster is slowing with time. Eventually, the cluster's gravity may stop the separation altogether, at which point the cluster will begin pulling in the galaxies of our Local Group, ultimately making them members of the cluster.

Similar processes are taking place on the outskirts of other large clusters of galaxies, where we see many galaxies whose speeds indicate that the cluster's gravity is pulling on them. Eventually, some or perhaps all of these galaxies will fall into the cluster. Thus, many clusters are still attracting galaxies, adding to the hundreds they already contain. On even larger scales, clusters themselves seem to be tugging on one another, hinting that they might be parts of even bigger gravitationally bound systems, called **superclusters**, that are still in the early stages of formation (Figure 22.12). But some structures are even larger than superclusters.

Gravity pulls galaxies into regions of the universe where the matter density is relatively high.

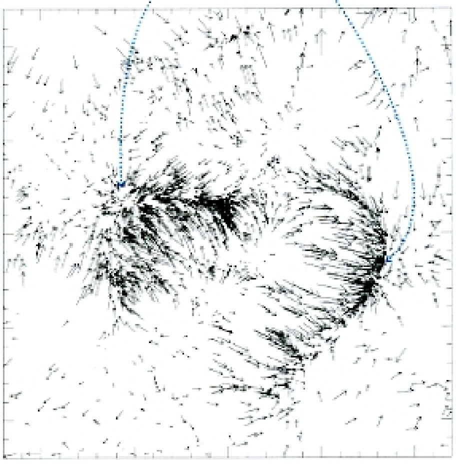


Figure 22.12 This graph represents the motions of galaxies attributable to effects of gravity. Each arrow represents the amount by which a galaxy's actual velocity (inferred from a combination of observations and modeling) differs from the velocity we'd expect it to have from Hubble's law alone. The Milky Way is at the center of the picture, which shows an area about 600 million light-years from side to side. (Only a representative sample of galaxies is shown.) Note how the galaxies tend to flow into regions where the density of galaxies is already high. These vast, high-density regions are probably superclusters in the process of formation.

THINK ABOUT IT

State whether each of the following is a gravitationally bound system, and explain why: (a) Earth; (b) a hurricane (on Earth); (c) the Orion Nebula; (d) a supernova.

• What are the largest structures in the universe?

Beyond about 300 million light-years from Earth, deviations from Hubble's law owing to gravitational tugs are insignificant compared with the universal expansion, so Hubble's law becomes our primary method for measuring galaxy distances [Section 20.2]. Using this law, astronomers can make maps of the distribution of galaxies in space. Such maps reveal **large-scale structures** much vaster than clusters of galaxies.

Mapping Large-Scale Structures Making maps of galaxy locations requires an enormous amount of data. A long-exposure photo showing galaxy positions is not enough, because it does not tell us the galaxy distances. We must also measure the redshift of each individual galaxy so that we can estimate its distance by applying Hubble's law. These measurements once required intensive labor, and up until just over a decade ago it took years of effort to map the locations of just a few hundred galaxies. However, astronomers have recently developed technology that allows redshift measurements for hundreds of galaxies during a single night of telescopic observation. As a result, we now have redshift measurements—and hence estimated distances—for many thousands of distant galaxies.

Figure 22.13 shows the distribution of galaxies in three slices of the universe, each extending farther out in distance. Our Milky Way Galaxy is located at the vertex at the far left, and each dot represents another entire galaxy of stars. The slice at the left comes from one of the first surveys of large-scale structures performed in the 1980s. This map, which required years of effort by many astronomers, dramatically revealed the complex structure of our corner of the universe. It showed that galaxies are not scattered randomly through space but are instead arranged in huge chains and sheets that span many millions of light-years. Clusters of galaxies are located at the intersections of these chains. Between these chains and sheets of galaxies lie giant empty regions called **voids**. The other two slices show data from the more recent Sloan Digital Sky Survey. The Sloan Survey has measured redshifts for nearly a million galaxies spread across about one-fourth of the sky.

Some of the structures in these pictures are amazingly large. The so-called Sloan Great Wall, clearly visible in the center slice, extends more than 1 billion light-years from end to end. Immense structures such as these apparently have not yet collapsed into randomly orbiting, gravitationally bound systems.

The universe may still be growing structures on these very large scales. However, there seems to be a limit to the size of the largest structures. If you look closely at the rightmost slice in Figure 22.13, you'll notice that the overall distribution of galaxies appears nearly uniform on scales larger than about a billion light-years. In other words, on very large scales the universe looks much the same everywhere, in agreement with what we expect from the *Cosmological Principle* [Section 20.2].

The Origin of Large Structures Why is gravity collecting matter on such enormous scales? Just as we suspect that galaxies formed from regions of slightly enhanced density in the early universe, we suspect that these larger structures were also regions of enhanced density. Galaxies, clusters, superclusters, and the Sloan Great Wall probably all started as mildly high-density regions of different sizes. The voids in the distribution of galaxies probably started as mildly low-density regions.

If this picture of structure formation is correct, then the structures we see in today's universe mirror the original distribution of dark matter very early in time. Supercomputer models of structure formation in the universe can now simulate the growth of galaxies, clusters, and larger structures from tiny density enhancements as the universe evolves (Figure 22.14). Models of extremely large regions

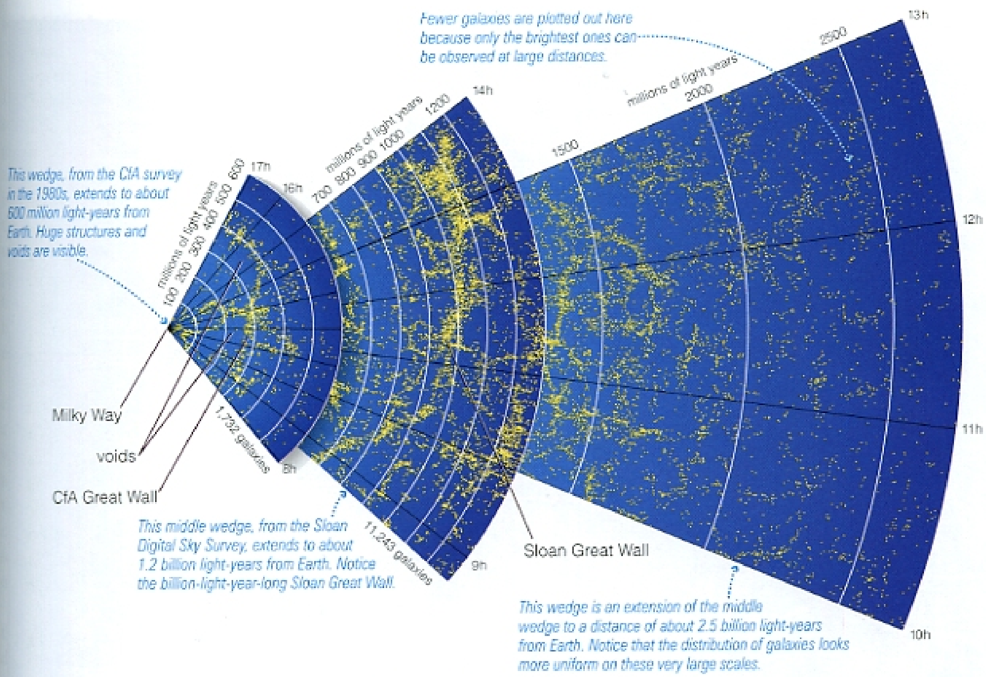


Figure 22.13 Each of these three wedges shows a "slice" of the universe extending outward from our own Milky Way Galaxy. The dots represent galaxies, shown at their measured distances from Earth. We see that galaxies are not scattered randomly but instead trace out long chains and sheets surrounded by huge voids containing very few galaxies. (The wedges are shown flat but actually are a few angular degrees in thickness; the CfA wedge at left does not actually line up with the two Sloan wedges.)

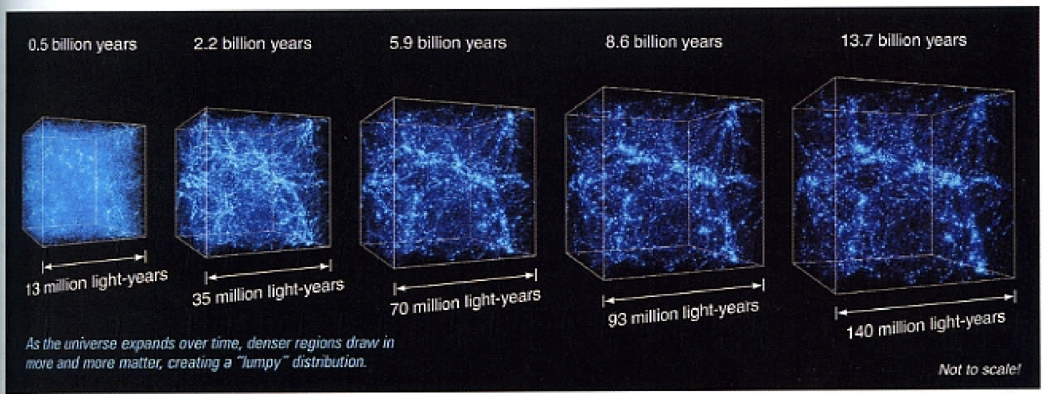


Figure 22.14 Interactive Figure Frames from a supercomputer simulation of structure formation. These five boxes depict the development of a cubical region that is now 140 million light-years across. The labels above the boxes give the age of the universe, and the labels below give the size of the box as it expands with time. Notice that the distribution of matter is only slightly lumpy when the universe is young (left frame). Structures grow more pronounced with time as the densest lumps draw in more and more matter.

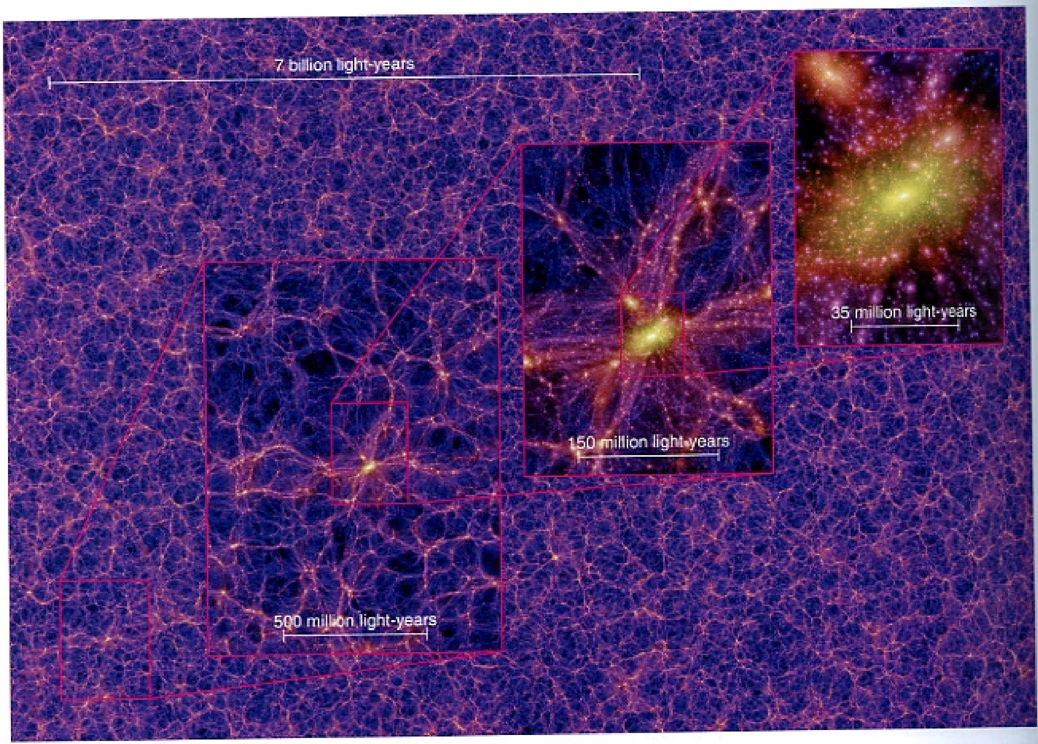


Figure 22.15 These images from an extremely large computer simulation illustrate the structure of dark matter in the universe. The largest image shows a region similar in size to our observable universe, and the image sequence zooms in on a massive cluster of galaxies. The images show structure as it would appear if we could see dark matter—the brightest clumps in the image represent the highest densities of dark matter in the computer simulation. Notice that the large-scale distribution of dark matter has a uniform web-like pattern.

reveal how dark matter should be distributed throughout the entire observable universe (Figure 22.15). The results of these models look remarkably similar to the slices of the universe in Figure 22.13, bolstering our confidence in this scenario. However, the models do not tell us *why* the universe started with these slight density enhancements—that is a topic for the next chapter. Nevertheless, it seems increasingly clear that these "lumps" in the early universe were the seeds of all the marvelous structures we see in the universe today.

Fate of the Universe Tutorial, Lessons 1–3

22.4 The Fate of The Universe

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

Robert Frost

We now arrive at one of the ultimate questions in astronomy: How will the universe end? Edwin Hubble's work established that the galaxies in the universe are rapidly flying away from one another [Section 20.2], but the gravitational pull of each galaxy on every other galaxy acts to slow the expansion. The possible outcomes would appear to fall into two general categories. If gravity is strong enough, the expansion will someday halt and the universe will begin collapsing, eventually ending in a cataclysmic crunch. Alternatively, if the expansion can overcome the pull of gravity, the universe will continue to expand forever, growing ever colder as its galaxies grow ever farther apart. The fate of the universe thus seems to boil down to a simple question: Is the universe expanding fast enough to escape its own gravitational pull and keep on expanding forever?

• Will the universe continue expanding forever?

Let's begin by considering the fate of the universe as it seemed just a few years ago, before the discoveries that suggested the presence of dark energy in the universe. In the absence of dark energy, we would expect gravity to be slowing the expansion of the universe with time. In that case, the fate of the universe hinges on the overall strength of the universe's gravitational pull. The strength of this pull depends on the density of matter in the universe: The greater the density, the greater the overall strength of gravity and the higher the likelihood that gravity will someday halt the expansion.

Precise calculations show that gravity can win out over expansion if the current density of the universe exceeds a seemingly minuscule 10^{-29} gram per cubic centimeter, which is roughly equivalent to a few hydrogen atoms in a volume the size of a closet. The precise density marking the dividing line between eternal expansion and eventual collapse is called the **critical density**. (Remember that for the moment, we are assuming a universe without dark energy.)

Observations of the luminous matter in galaxies show that the mass contained in stars falls far short of the critical density. The visible parts of galaxies contribute about 0.5% of the matter density needed to halt the universe's expansion. The fate of the universe would thus seem to rest with the dark matter. Is there enough dark matter to halt the expansion of the universe?

Because stars seem to contribute about 0.5% of the matter density needed to halt the expansion, the expansion could halt only if the total mass of dark matter were at least 200 times that of the mass in stars. Our studies of individual galaxies suggest that they contain at least 10 times as much dark matter as matter in stars, and studies of clusters of galaxies raise that number further to about 50 times as much dark matter as matter in stars. However, this is still only about a quarter of the amount of dark matter needed to halt the expansion. Thus, if the proportion of dark matter in the universe at large is similar to that in clusters, the universe seems destined to expand forever. For gravity to reverse the expansion and pull the universe back together, even more dark matter would have to lie beyond the boundaries of clusters.

If large-scale structures really did contain a higher proportion of dark matter than do clusters, the influence of that extra dark matter should show up in the velocities of galaxies near those large-scale structures: Larger amounts of dark matter would be causing greater deviations from Hubble's law. As of 2005, however, studies of galaxy velocities are holding the line near the value we infer from clusters, which is about 25% of the critical density required to reverse the expansion. If that is the case, the universe seems destined to expand forever, even if there is no dark energy affecting the rate of expansion.

• Is the expansion of the universe accelerating?

In the past few years, observations of distant white dwarf supernovae have enabled us to probe the fate of the universe in an entirely new way. Because white dwarf supernovae are such good standard candles [Section 20.2], we can use them to determine whether gravity has been slowing the universe's expansion, as it must if the universe is destined to end in a cataclysmic crunch. However, the astronomers who set out to measure gravity's influence over the universe by observing supernovae discovered something quite unexpected.

Instead of slowing because of gravity, the expansion of the universe appears to be speeding up, suggesting that some mysterious repulsive force—the so-called *dark energy*—is pushing all the universe's galaxies apart. This discovery, if it holds up to further scrutiny, has far-reaching implications for both the fate of the universe and our understanding of the forces that govern its behavior on large scales. To understand the evidence for an accelerating expansion, we must become more familiar with the possible futures of the universe.

Four Expansion Patterns Astronomers subdivide the two general possibilities for the fate of the universe—expanding forever or someday collapsing—into four broad categories. Each represents a particular pattern of change in the future expansion rate (Figure 22.16). We will call these four possible expansion patterns *recollapsing, critical, coasting,* and *accelerating*. The first three possibilities assume that gravity is the only force that affects the expansion rate of the universe, while the fourth adds a repulsive force (dark energy) that opposes gravity:

- **A recollapsing universe:** If there is no dark energy and the matter density of the universe is *larger* than the critical density, then the collective gravity of all its matter will eventually halt the universe's expansion and reverse it. The galaxies will come crashing back together, and the entire universe will end in a fiery "Big Crunch." We call this a recollapsing universe because the final state, with all matter collapsed together, would look much like the state in which the universe began in the Big Bang. (A recollapsing universe is sometimes called a *closed universe*, because the overall geometry of spacetime would close upon itself like the surface of a sphere [Section S3.2].)
- **A critical universe:** If there is no dark energy and the matter density of the universe *equals* the critical density, then the collective gravity of all its matter is exactly the amount needed to balance the expansion. The universe will never collapse but will expand more and more slowly as time progresses. We call this a critical universe because its density is the critical density. (Mathematically speaking, a critical universe stops expanding after

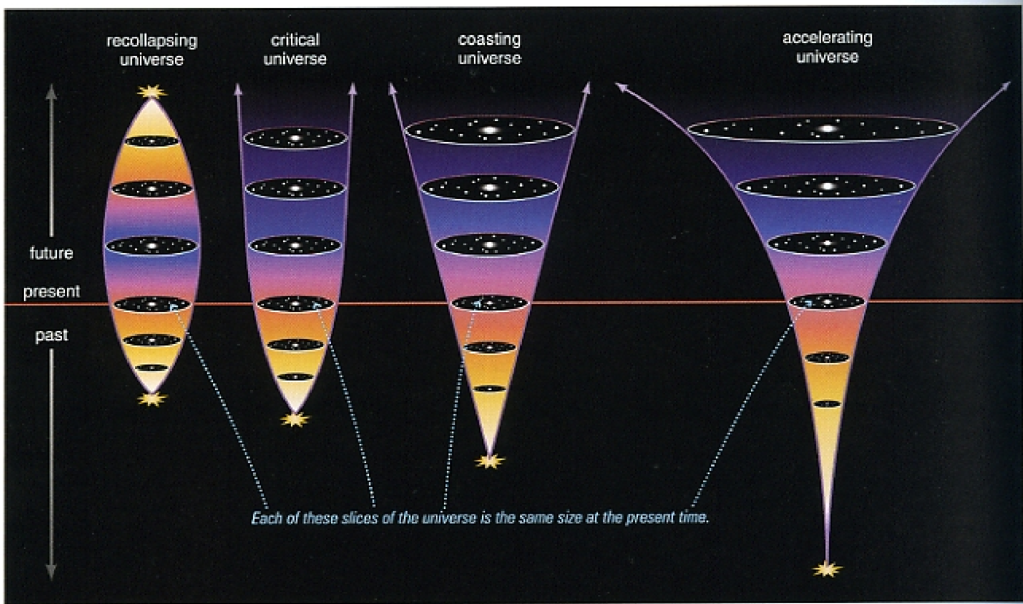


Figure 22.16 Four models for the fate of the universe. Each diagram shows how the size of a circular slice of the universe changes with time in a particular model. The slices are the same size at the present time, marked by the red line, but the models make different predictions about the sizes of the slices in the past and future. The first three cases assume that there is no dark energy, so that the fate of the universe depends only on how its actual density compares to the critical density. The last case assumes that a repulsive force—the so-called dark energy—is accelerating the expansion over time. (The diagram assumes continuous acceleration, but it is also possible that the universe initially slowed before the acceleration began.)

infinite time, and its overall geometry is "flat"—like the surface of a table but in more dimensions. Thus, a critical universe is one example of what astronomers call a *flat universe.*)

- **A coasting universe:** If there is no dark energy and the matter density of the universe is *smaller* than the critical density, then the collective gravity of all its matter cannot halt the expansion. The universe will keep expanding forever, with little change in its rate of expansion; that is, the expansion will continue to coast forever. (A coasting universe is sometimes called an *open universe*, because its overall geometry is more like the open surface of a saddle than like the closed surface of a sphere.)
- **An accelerating universe:** If dark energy exerts a repulsive force that causes the expansion of the universe to *accelerate* with time, then the expansion rate will grow with time. Galaxies will recede from one another with increasing speed, and the universe will become cold and dark more quickly than it would in a coasting universe. (Depending on the strength of gravity relative to the repulsive force, the overall geometry of an accelerating universe could be flat, open, or closed. As we'll discuss in Chapter 23, current evidence suggests a flat geometry for this case.)

THINK ABOUT IT

Do you think that one of the potential fates of the universe is preferable to the others? Why or why not?

Evidence for Acceleration Figure 22.17 illustrates how the average distance between galaxies should change with time for each possibility. The lines for the accelerating, coasting, and critical universes always continue upward as time increases, because in these cases the universe is always expanding. The steeper the slope, the faster the expansion. In the recollapsing case, the line begins on an upward slope but eventually turns around and declines as the universe contracts. All the lines pass through the same point and have the same slope at the moment labeled "now," because the current separation between galaxies and the current expansion rate in each case must agree with observations of the present-day universe.

Note that the age that we infer for the universe from its expansion rate differs in each case. A recollapsing universe requires the least amount of time to arrive at the current separation between galaxies—the example in Figure 22.17 goes from zero separation to the current separation in less than 5 billion years. The cases for which gravity is less important require more time to achieve the current separa-

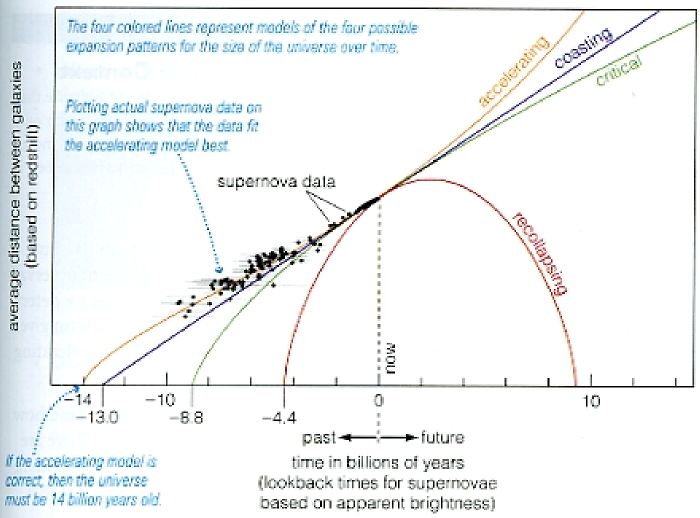


Figure 22.17 Data from white dwarf supernovae are shown along with four possible models for the expansion of the universe. Each curve shows how the average distance between galaxies changes with time for a particular model. A rising curve means that the universe is expanding, and a falling curve means that the universe is contracting. Notice that the supernovae data fit the accelerating universe better than the other models.

tion between galaxies. The ages that we would infer from the examples in Figure 22.17 are 8.8 billion years for a critical universe, 13 billion years for a coasting universe, and around 14 billion years for an accelerating universe.

This relationship between the age of the universe and its expansion pattern enables us to determine the expansion pattern from observations of white dwarf supernovae. Because these supernovae are so bright and make such excellent standard candles, we can identify them and measure their distances and redshifts even when they are more than halfway across the observable universe. The distance we measure essentially tells us the lookback time to the supernova, while its redshift tells us how much the universe has expanded since the time of the supernova explosion. Combining these two pieces of information for supernova explosions at different times in the past therefore reveals how fast the universe was expanding over that entire time period.

Observations of such distant supernovae are still very difficult, but we have some data that are plotted as dots in Figure 22.17. Although there is some scatter in these data,

SPECIAL TOPIC Einstein's Greatest Blunder

Shortly after Einstein completed his general theory of relativity in 1915, he found that it predicted that the universe could not be standing still: The mutual gravitational attraction of all the matter would make the universe collapse. Because Einstein thought at the time that the universe should be eternal and static, he decided to alter his equations. In essence, he inserted a "fudge factor" called the *cosmological constant* that acted as a repulsive force to counteract the attractive force of gravity.

Had he not been so convinced that the universe should be standing still, Einstein might instead have come up with the correct explanation for why the universe is not collapsing: because it is still expanding from the event of its birth. After Hubble discovered the universal expansion, Einstein supposedly called his invention of the cosmological constant "the greatest blunder" of his career.

Recently, however, astronomers have begun to take the idea of a cosmological constant more seriously. In the mid-1990s, a few observations suggested that the oldest stars were slightly older than the age of the universe derived from Hubble's constant under the assumption that gravity is the only force affecting the universe's expansion. Clearly, stars cannot be older than the universe. If these observations were being interpreted correctly, the universe had to be older than Hubble's constant implies. If the expansion rate has accelerated, so that the universe is expanding faster today than it was in the past, then the age of the universe would be greater than that ordinarily found from Hubble's constant (see Figure 22.16). What could cause the expansion of the universe to accelerate over time? The repulsive force represented by a cosmological constant, of course.

Further study of the troubling observations has shown that the oldest stars probably are *not* older than the age of the universe derived from Hubble's constant. However, measurements of distances to high-redshift galaxies using white dwarf supernovae as standard candles now suggest that the expansion *is* accelerating. A cosmological constant arising from dark energy could account for this startling finding, but we'll need more observations before we can be sure it is correct. Interestingly, the observations we currently have indicate that dark energy has properties identical to the repulsive force that Einstein originally proposed. The amount of dark energy in each volume of space seems to remain unchanged while the universe expands, as if the vacuum of space itself were constantly rippling with energy [Section S4.5]. Einstein's greatest blunder, it seems, just won't go away.

they appear to fit the curve for an accelerating universe better than any of the other models, and they do not fit either a critical or a recollapsing universe. In other words, the observations to date seem to favor an accelerating universe.

Exactly why the expansion of the universe might be accelerating remains a deep mystery. No known force would act to push the universe's galaxies apart, and an enormous amount of energy would be required. Of course, our lack of understanding does not stop us from giving a name to the repulsive force that is causing the acceleration, and we have already discussed why it is often dubbed *dark energy*. Keep in mind, however, that we do not yet have any idea of what the dark energy might actually be. Nevertheless, if dark energy really exists, it is the most prevalent form of energy in the universe, outstripping the total mass-energy of all the matter in the universe—including the dark matter. Only continued observations will tell us whether the dark energy is real or an artifact of our still-limited data.

A Never-Ending Expansion? Whether or not the dark energy exists, and whatever dark energy might turn out to be, it now seems likely that the universe is indeed doomed to expand forever, its galaxies receding ever more quickly into an icy, empty future. After all, our examination of the strength of gravity showed that it is too weak to stop the expansion even without dark energy, and the acceleration due to dark energy would seem only to seal this fate. Some scientists even hypothesize that the dark energy could eventually cause galaxies, stars, and planets to break apart and disperse with the never-ending expansion.

However, before we convince ourselves that we now know the fate of the universe, we should bear in mind that forever is a very long time. The universe may hold other surprises that we haven't yet discovered, surprises that might force us to rethink what might happen between now and the end of time.

This is the way the world ends
This is the way the world ends
This is the way the world ends
Not with a bang but a whimper.

From *The Hollow Men* by T. S. Eliot

THE BIG PICTURE

Putting Chapter 22 into Context

We have found that there may be much more to the universe than meets the eye. Dark matter too dim for us to see seems to far outweigh the stars, and a mysterious dark energy may be even more prevalent. Here are some key "big picture" points to remember about this chapter:

- Dark matter and dark energy sound very similar, but they are each hypothesized to explain different observations. Dark matter is thought to exist because we detect its gravitational influence. "Dark energy" is a term given to whatever strange, repulsive force may be accelerating the expansion of the universe.
- Either dark matter exists, or we do not understand how gravity operates across galaxy-size distances. There are many reasons to be confident about our understanding of gravity, leading most astronomers to conclude that dark matter is real.
- Dark matter seems by far to be the most abundant form of mass in the universe. We still do not know what it is, but we suspect it is largely made up of some type of as-yet-undiscovered subatomic particles.
- If dark matter is indeed the dominant source of gravity in the universe, then it is the glue that binds together galaxies, clusters, superclusters, and other large-scale structures in the universe. All this structure has probably grown from regions in the early universe where the density of dark matter was slightly enhanced.
- The fate of the universe depends on whether gravity can ever halt the present expansion. The total strength of gravity seems too weak to do so even when we account for dark matter, and the evidence indicating that the expansion is accelerating only reinforces the idea that expansion will never cease.

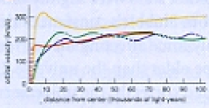
SUMMARY OF KEY CONCEPTS

22.1 Unseen Influences in the Cosmos

- **What do we mean by dark matter and dark energy?** **Dark matter** and **dark energy** have never been directly observed, but each has been proposed to exist because it seems the simplest way to explain a set of observed motions in the universe. "Dark matter" is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds. "Dark energy" is the name given to whatever may be causing the expansion of the universe to accelerate.

22.2 Evidence for Dark Matter

- **What is the evidence for dark matter in galaxies?** The orbital velocities of stars and gas clouds



in galaxies do not change much with distance from the center of the galaxy. Applying Newton's laws of gravitation and motion to these orbits leads to the conclusion that the total mass of a galaxy is far larger than the mass of its stars. Because no detectable visible light is coming from this matter, we call it **dark matter.**

- **What is the evidence for dark matter in clusters of galaxies?** We have three different ways of measuring the amount of dark matter in clusters of galaxies: from galaxy orbits, from the temperature of the hot gas in clusters, and from the **gravitational lensing** predicted by Einstein. All these methods are in agreement, indicating that the total mass of a cluster is about 50 times the mass of its stars, implying huge amounts of dark matter.

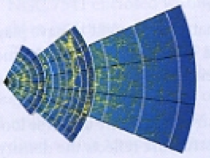
- **Does dark matter really exist?** We infer that dark matter exists from its gravitational influence on the matter we can see, leaving two possibilities: Either dark matter exists, or there is something wrong with our understanding of gravity. We cannot rule out the latter possibility, but we have good reason to be confident about our current understanding of gravity and the idea that dark matter is real.

- **What might dark matter be made of?** Some of the dark matter could be ordinary or **baryonic matter** in the form of dim stars or planetlike objects, but there does not appear to be enough ordinary matter to account for all the dark matter. Most of it is probably extraordinary or **nonbaryonic matter** consisting of undiscovered particles that we call **WIMPs.**

22.3 Structure Formation

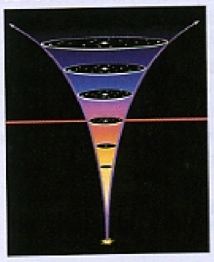
- **What is the role of dark matter in galaxy formation?** Because most of a galaxy's mass is in the form of dark matter, the gravity of that dark matter is probably what formed protogalactic clouds and then galaxies from slight density enhancements in the early universe.

- **What are the largest structures in the universe?** Galaxies appear to be distributed in gigantic chains and sheets that surround great voids. These giant structures trace their origin directly back to regions of slightly enhanced density early in time.

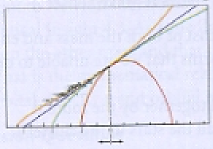


22.4 The Fate of the Universe

- **Will the universe continue expanding forever?** Even before we consider the possibility of a mysterious dark energy, the evidence points to eternal expansion. The **critical density** is the average matter density that the universe would need for the strength of gravity to eventually halt the expansion. The overall matter density of the universe appears to be only about 25% of the critical density.



- **Is the expansion of the universe accelerating?** Observations of distant supernovae indicate that the expansion of the universe is speeding up. No one knows the nature of the mysterious force (dark energy) that could be causing this acceleration.



EXERCISES AND PROBLEMS

For instructor-assigned homework go to MasteringASTRONOMY www.masteringastronomy.com

Review Questions

Short-Answer Questions Based on the Reading

1. Define *dark matter* and *dark energy*, and clearly distinguish between them. What types of observations have led scientists to propose the existence of each of these unseen influences?
2. What is a *rotation curve?* Describe the rotation curve of the Milky Way, and explain how it indicates the presence of large amounts of dark matter.
3. How do we construct rotation curves for other spiral galaxies? What do they tell us about the galaxy masses and dark matter?
4. How do we measure the masses of elliptical galaxies? What do these masses lead us to conclude about dark matter in elliptical galaxies?
5. Briefly describe the three different ways of measuring the mass of a cluster of galaxies. Do the results from the different methods agree? What do they tell us about dark matter in galaxy clusters?
6. What is *gravitational lensing?* Why does it occur? How can we use it to estimate the masses of lensing objects?
7. Briefly explain why the conclusion that dark matter exists rests on assuming that we understand gravity correctly. Is it possible that our understanding of gravity is not correct? Explain.
8. In what sense is dark matter "dark"? Briefly explain why objects like you, planets, and even dim stars could qualify as dark matter.
9. What do we mean by *MACHOs?* How can we search for them? Briefly describe why these searches suggest that starlike (or planetlike) objects and black holes *cannot* account for all the dark matter in the halo of our galaxy.

10. Explain what we mean when we say that a neutrino is a *weakly interacting particle*. Why can't the dark matter in galaxies be made of neutrinos?
11. What do we mean by *WIMPs?* Why does it seem likely that dark matter consists of these particles, even though we do not yet know what they are?
12. Briefly explain why dark matter is thought to have played a major role in the formation of galaxies and larger structures in the universe. What evidence suggests that large structures are still forming?
13. What does the large-scale structure of the universe look like? Explain why we think this structure reflects the density patterns of the early universe.
14. What do we mean by the *critical density* of the universe? According to current evidence, how does the actual density of matter in the universe compare to the critical density?
15. Describe and compare four possible patterns for the expansion of the universe: recollapsing, critical, coasting, and accelerating. Observationally, how can we decide which of the four possible expansion models is the right one?
16. Assuming the accelerating expansion of the universe is real, what does it imply for the fate of the universe? What does current evidence suggest for the fate of the universe if the acceleration is not real? Explain.

Test Your Understanding

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain your reasoning. (For an example, see Chapter 1, "Does It Make Sense?")

17. Strange as it may sound, most of both the mass and energy in the universe may take forms that we are unable to detect directly.
18. A cluster of galaxies is held together by the mutual gravitational attraction of all the stars in the cluster's galaxies.
19. We can estimate the total mass of a cluster of galaxies by studying the distorted images of galaxies whose light passes through the cluster.
20. Clusters of galaxies are the largest structures that we have so far detected in the universe.
21. The primary evidence for an accelerating universe comes from observations of young stars in the Milky Way.
22. There is no doubt remaining among astronomers that the fate of the universe is to expand forever.
23. Dark matter is called "dark" because it blocks light from traveling between the stars.
24. If the universe has more dark matter than we think, then it is also younger than we think.
25. The distance to a white dwarf supernova with a particular redshift is larger in an accelerating universe than in a universe with no acceleration.
26. If dark matter consists of WIMPs, then we should be able to observe photons produced by collisions between these particles.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Dark matter is inferred to exist because: (a) we see lots of dark patches in the sky. (b) it explains how the expansion of the universe can be accelerating. (c) we can observe its gravitational influence on visible matter.
28. Dark energy has been hypothesized to exist in order to explain: (a) observations suggesting that the expansion of the universe is accelerating. (b) the high orbital speeds of stars far from the center of our galaxy. (c) explosions that seem to create giant voids between galaxies.
29. The flat part of the Milky Way Galaxy's rotation curve tells us that stars in the outskirts of the galaxy: (a) orbit the galactic center just as fast as stars closer to the center. (b) rotate rapidly on their axes. (c) travel in straight, flat lines rather than elliptical orbits.
30. Strong evidence for the existence of dark matter comes from observations of: (a) our solar system. (b) the center of the Milky Way. (c) clusters of galaxies.
31. A photograph of a cluster of galaxies shows distorted images of galaxies that lie behind it at greater distances. This is an example of what astronomers call: (a) dark energy. (b) spiral density waves. (c) a gravitational lens.
32. Based on the observational evidence, is it possible that dark matter doesn't really exist? (a) No, the evidence for it is too strong to think it could be in error. (b) Yes, but only if there is something wrong with our current understanding of how gravity should work on large scales. (c) Yes, but only if all the observations themselves are in error.
33. Based on current evidence, which of the following is considered a likely candidate for the majority of the dark matter in galaxies? (a) subatomic particles that we have not yet detected in particle physics experiments (b) swarms of relatively dim, red stars (c) supermassive black holes
34. Which region of the early universe was most likely to become a galaxy? (a) a region whose matter density was lower than average (b) a region whose matter density was higher than average (c) a region with an unusual concentration of dark energy
35. The major evidence for the idea that the expansion of the universe is accelerating comes from observations of: (a) white dwarf supernovae. (b) the orbital speeds of stars within galaxies. (c) the evolution of quasars.
36. Which of the following possible types of universe would *not* expand forever? (a) a critical universe (b) an accelerating universe (c) a recollapsing universe

Investigate Further

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

37. *Dark Matter.* Overall, how convincing do you consider the case for the existence of dark matter? Write a short essay in which you describe what we mean by dark matter, describe the evidence for its existence, and discuss your opinion about the strength of the evidence.

38. *Dark Energy.* Overall, how convincing do you consider the case for the existence of dark energy? Write a short essay in which you describe what we mean by dark energy, describe the evidence for its existence, and discuss your opinion about the strength of the evidence.

39. *The Future Universe.* Based on current evidence concerning the growth of structure in the universe, briefly describe what you would expect the universe to look like on large scales about 10 billion years from now.

40. *Dark Matter and Life.* State and explain at least two reasons one might argue that dark matter is (or was) essential for life to exist on Earth.

41. *Rotation Curves.* Draw and label a rotation curve for each of the following three hypothetical situations. Make sure the radius axis has approximate distances labeled.
    a. All the mass of the galaxy is concentrated in the center of the galaxy.
    b. The Galaxy has a constant mass density inside 20,000 light-years, and zero density outside that.
    c. The galaxy has a constant mass density inside 20,000 light-years, and its enclosed mass increases proportionally to the radius outside that.

42. *Dark Energy and Supernova Brightness.* When astronomers began measuring the brightnesses and redshifts of distant white dwarf supernovae, they expected to find that expansion of the universe was slowing down. Instead they found that it was speeding up! Were the distant supernovae brighter or fainter than expected? Explain why. (*Hint:* In Figure 22.16, the position of a supernova point on the vertical axis depends on its redshift. Its position on the horizontal axis depends on its brightness—supernovae seen farther back in time are not as bright as those seen closer in time.)

43. *What Is Dark Matter?* Describe at least three possible constituents of dark matter. Explain how we would expect each to interact with light, and how we might go about detecting its existence.

44. *Alternative Gravity.* How would gravity have to be different in order to explain the rotation curves of galaxies without the need for dark matter? Would gravity need to be stronger or weaker than expected at very large distances? Explain.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

45. *White Dwarf M/L.* What is the mass-to-light ratio of a 1 M_{Sun} white dwarf with luminosity 0.001 L_{Sun}?

46. *Supergiant M/L.* What is the mass-to-light ratio of a 30 M_{Sun} supergiant star with luminosity 300,000 L_{Sun}?

47. *Solar System M/L.* What is the mass-to-light ratio of the solar system?

48. *Mass from Rotation Curve.* Study the rotation curve for the spiral galaxy NGC 7541, which is shown in Figure 22.4.
    a. Use the orbital velocity law to determine the mass (in solar masses) of NGC 7541 enclosed within a radius of 30,000 light-years from its center. (*Hint:* 1 light-year = 9.461×10^{15} m.)
    b. Use the orbital velocity law to determine the mass of NGC 7541 enclosed within a radius of 60,000 light-years from its center.
    c. Based on your answers to parts (a) and (b), what can you conclude about the distribution of mass in this galaxy?

49. *Weighing a Cluster.* A cluster of galaxies has a radius of about 5.1 million light-years (4.8×10^{22} m) and an intracluster medium with a temperature of 6×10^7 K. Estimate the mass of the cluster. Give your answer in both kilograms and solar masses. Suppose the combined luminosity of all the stars in the cluster is 8×10^{12} L_{Sun}. What is the cluster's mass-to-light ratio?

50. *Cluster Mass from Hot Gas.* The gas temperature of the Coma cluster of galaxies is about 9×10^7 K. What is the mass of this cluster within 15 million light-years of the cluster center?

51. *How Many MACHOs?* Imagine a galaxy whose stars are all identical to the Sun but that has an overall mass-to-light ratio of 30.
    a. What is the ratio of dark matter to luminous matter in this galaxy?
    b. Suppose all the dark matter consists of MACHOs similar to Jupiter, each with a mass of 0.001 solar mass. How many of these MACHOs must the galaxy contain for each ordinary star? Explain.

52. *From Newton to Dark Matter.* Show that the equation $M = r \times v^2/G$ from Mathematical Insight 22.2 is equivalent to Newton's version of Kepler's third law from Mathematical Insight 4.3. Assume that one mass is much larger than the other mass and that the orbit is circular. (*Hint:* What is the mathematical relationship between period p and orbital velocity v and orbital radius r for a circular orbit?)

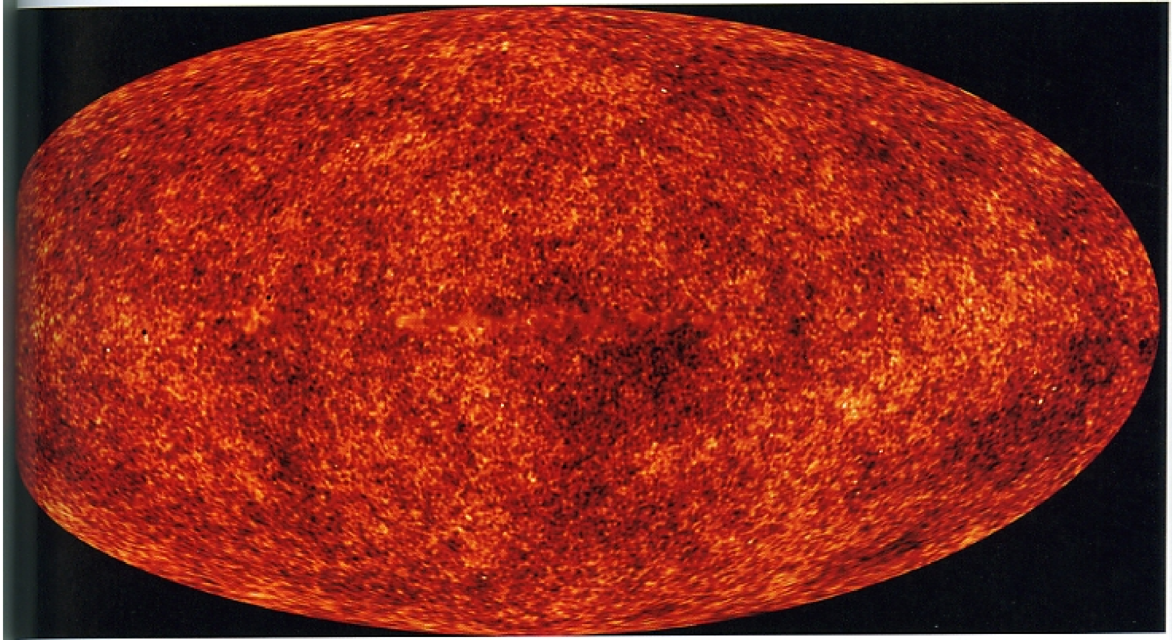
Discussion Questions

53. *Dark Matter or Revised Gravity.* One possible explanation for the evidence we find for dark matter is that we are currently using the wrong law of gravity to measure the masses of very large objects. If we really do misunderstand gravity, then many fundamental theories of physics, including Einstein's theory of general relativity, will need to be revised. Which explanation for our observations do you find more appealing, dark matter or revised gravity? Explain why. Why do you suppose most astronomers find dark matter more appealing?

54. *Our Fate.* Scientists, philosophers, and poets alike have speculated on the fate of the universe. How would you prefer the universe as we know it to end, in a "Big Crunch" or through eternal expansion? Explain the reasons behind your preference.

23

The Beginning of Time



LEARNING GOALS

23.1 The Big Bang
- What were conditions like in the early universe?
- What is the history of the universe according to the Big Bang theory?

23.2 Evidence for the Big Bang
- How do we observe the radiation left over from the Big Bang?
- How do the abundances of elements support the Big Bang theory?

23.3 The Big Bang and Inflation
- What aspects of the universe were originally unexplained by the Big Bang model?
- How does inflation explain these features of the universe?
- How can we test the idea of inflation?

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

Somewhere, something incredible is waiting to be known.
Carl Sagan

The universe has been expanding for about 14 billion years. During that time, matter has collected into galaxies and stars have formed in those galaxies, producing heavy elements that have been recycled into later generations of stars. One of these late-coming stars formed about 4.6 billion years ago, in a remote corner of a galaxy called the Milky Way. This star was born with a host of planets that formed in a flattened disk surrounding it. One of these planets soon became covered with life that gradually evolved into ever more complex forms. Today, the most advanced life-form on this planet, human beings, can look back on this series of events and marvel at how the universe created conditions suitable for life.

To this point in the book, we have discussed how the matter produced in the early universe gradually assembled into planets, stars, and galaxies. However, we have not yet answered one big question: Where did the *matter itself* come from? To answer this ultimate question, we must go beyond the most distant galaxies and even beyond what we can see near the horizon of the universe. We must go back not only to the origins of matter and energy but to the beginning of time itself.

Hubble's Law Tutorial, Lessons 1–3

23.1 The Big Bang

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

Unfortunately, we cannot see back to the very beginning of time. Light from the most distant galaxies shows us what the universe looked like when it was 1 or 2 billion years old. Beyond these galaxies, we have not yet found any objects shining brightly enough for us to see them. Ultimately, we face an even more fundamental problem. The universe is filled with a faint glow of radiation that appears to be the remnant heat of the Big Bang. This faint glow is light that has traveled freely through space since the universe was about 380,000 years old, which is when the universe first became transparent to light. Before that time, light could not pass freely through the universe, so there is no possibility of seeing light from earlier times. Thus, just as we must rely on mathematical modeling to determine what the Sun is like on the inside, we must also use modeling to investigate what the universe was like during its earliest moments.

• What were conditions like in the early universe?

Scientific models of the conditions that prevailed in the early universe are based on fundamental principles of physics. The universe is cooling and becoming less dense as it expands, so it must have been hotter and denser in the past. Calculating exactly how hot and dense the universe must have been when it was more compressed is similar to calculating the temperature and density of gas in a balloon when you squeeze it, except that the conditions become much more extreme. Figure 23.1 shows just how hot the universe was during its earliest moments, according to such calculations.

The universe was so hot during the first few seconds that photons could transform themselves into matter, and vice versa, in accordance with Einstein's formula $E = mc^2$ [Section 4.3]. Reactions that create and destroy matter are now relatively rare in the universe at large, but physicists can reproduce many such reactions in their laboratories.

One such reaction is the creation or destruction of an *electron-antielectron pair* (Figure 23.2). When two photons collide with a total energy greater than twice the mass-energy of an electron (the electron's mass times c^2), they can create two brand-new particles: a negatively charged electron and its positively charged twin, the *antielectron* (also known as a *positron*). The electron is a particle of

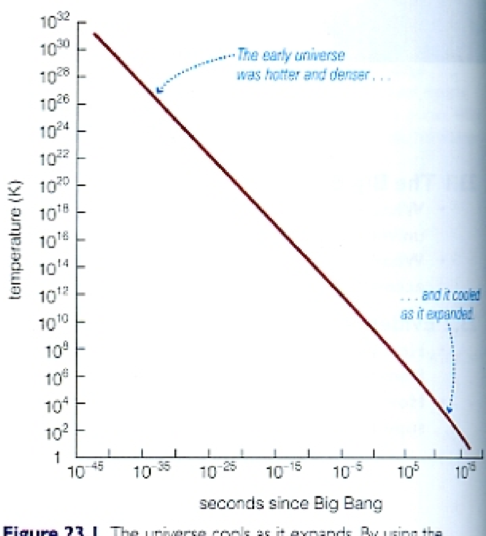


Figure 23.1 The universe cools as it expands. By using the laws of physics and the current temperature of the universe (about 3 K), we can calculate how hot the universe must have been in the past. This graph shows the results. Notice that both axis scales use powers of 10. (The graph extends to the present: 10^{10} yr ≈ 3×10^{17} s.)

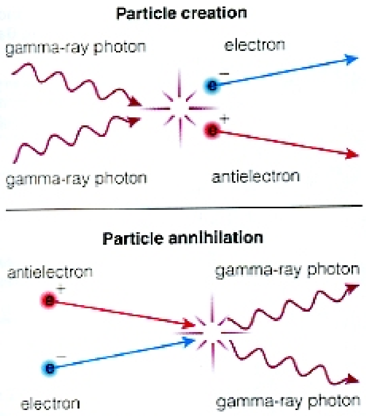


Figure 23.2 Electron-antielectron creation and annihilation. Reactions like these constantly converted photons to particles and vice versa in the early universe.

matter, and the antielectron is a particle of **antimatter**. The reaction that creates an electron-antielectron pair also runs in reverse. When an electron and an antielectron meet, they *annihilate* each other totally, transforming all their mass-energy back into photon energy. In order to conserve both energy and momentum, an annihilation reaction must produce two photons instead of just one.

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

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

• What is the history of the universe according to the Big Bang theory?

The **Big Bang theory**—the scientific theory of the universe's earliest moments—is based on applying known and tested laws of physics to the idea that all we see today, from Earth to the cosmic horizon, began as an incredibly tiny, hot, and dense collection of matter and radiation. The Big Bang theory describes how expansion and cooling of this unimaginably intense mixture of particles and photons could have led to the present universe of stars and galaxies, and it explains several aspects of today's universe with impressive accuracy. We will discuss the evidence supporting the Big Bang theory later in this chapter. First, in order to help you understand the significance of the evidence, we'll examine the history of the universe according to this theory.

Figure 23.3 summarizes the story by dividing the overall history of the universe into a series of *eras*, or time periods. (Some scientists further subdivide the eras described here.) Each era is distinguished from the next by some major change in the conditions of the universe. You'll find it easiest to keep track of the various eras if you refer back to this figure as we discuss each era in detail. Notice that most of the key events in the history of the universe occurred in a very short period of time. It will take you longer to read this chapter than it took the universe to progress through the first five eras we will discuss, by which point the chemical composition of the universe had already been determined.

The Planck Era As we work our way back through time, we ultimately reach the limit of our current scientific ability to understand the physical conditions when the universe was an incomprehensibly young 10^{-43} second old. This instant in time is called the *Planck time* after physicist Max Planck, one of the founders of the science of quantum mechanics. We refer to all times prior to the Planck time as the **Planck era**; that is, the Planck era represents the first 10^{-43} second in the history of the universe.

Current theories cannot adequately describe the extreme conditions that must have existed during the Planck era. According to the laws of quantum mechanics, there must have been substantial energy fluctuations from point to point in the very early universe. Because energy and mass are equivalent, Einstein's theory of general relativity tells us that these energy fluctuations must have generated a rapidly changing gravitational field that randomly warped space and time. During the Planck era, these random energy fluctuations were so large that our current theories are inadequate to describe what might have been happening. In essence, the problem is that we do not yet have a theory that links quantum mechanics (our successful theory of the very small) and general relativity (our successful theory of the very big). Perhaps someday we will be able to merge these theories of the very small and the very big into a single "theory of everything" (see Special Topic, p. 463). Until that happens, science cannot describe the universe before the Planck time.

The GUT Era Understanding the transition that marked the beginning of the next era requires thinking in terms of the *forces* that operate in the universe. Everything that happens in the universe today is governed by four distinct

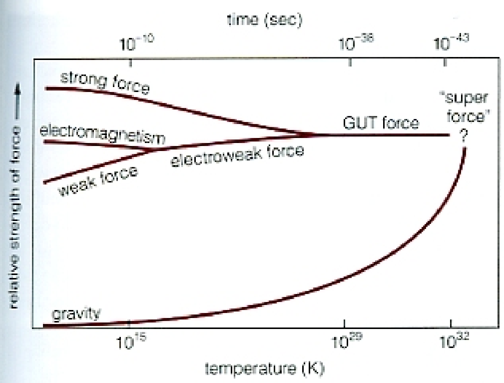


Figure 23.4 The four forces are distinct at low temperatures but may merge at very high temperatures.

particles such as neutrinos or WIMPs (weakly interacting massive particles [Section 22.2]).

Although the four forces behave quite differently from one another, we now believe that they are actually just different aspects of a smaller number of more fundamental forces, probably only one or two (Figure 23.4). At the high temperatures that prevailed in the early universe, the four forces were not so distinct as they are today.

As an analogy, think about ice, liquid water, and water vapor. These three substances are quite different from one another in appearance and behavior, yet they are just different phases of the single substance H_2O. In a similar way, experiments have shown that the electromagnetic and weak forces lose their separate identities under conditions of very high temperature or energy and merge together into a single **electroweak force.** At even higher temperatures and energies, the electroweak force may merge with the strong force and ultimately with gravity. Theories that predict the merger of the electroweak and strong forces are called **grand unified theories,** or **GUTs** for short. Thus, the merger of the strong, weak, and electromagnetic forces is often called the *GUT force.* Many physicists suspect that at even higher energies, the GUT force and gravity merge into a single "super force" that governs the behavior of everything. (Among the names you may hear for theories linking all four forces are *supersymmetry, superstrings,* and *supergravity.*)

Calculations from general relativity and quantum mechanics suggest that this unified "super force" may have reigned in the universe during the Planck era. If so, the Planck time (10^{-43} second) marks the instant when gravity became distinct from the other three forces, which were still merged as the GUT force. By analogy to ice crystals forming as a liquid cools, we say that gravity "froze out" at the Planck time. The universe subsequently entered the **GUT era,** when two forces operated in the universe: gravity and the GUT force.

The GUT era is thought to have lasted but a tiny fraction of a second, coming to an end when the universe had cooled to 10^{29} K at an age of about 10^{-38} second. Grand unified theories predict that the strong force froze out from the GUT force at this point, leaving three forces operating in the universe: gravity, the strong force, and the electroweak force. The freezing out of the strong force may have released an enormous amount of energy. This energy release may have caused the universe to undergo a sudden and dramatic expansion that we call **inflation.** In the space of a mere 10^{-36} second, pieces of the universe the size of an atomic nucleus may have grown to the size of our solar system. Inflation sounds bizarre, but as we will discuss later, it explains several important features of today's universe.

The Electroweak Era The end of the GUT era marked the beginning of the **electroweak era,** so named because the electromagnetic and weak forces were still unified in the electroweak force. Intense radiation filled all of space, as it had since the Planck era, spontaneously producing matter and antimatter particles that almost immediately annihilated each other and turned back into photons. The universe continued to expand and cool throughout the electroweak era, dropping to a temperature of 10^{15} K when it reached an age of 10^{-10} second. This temperature is still 100 million times hotter than the temperature in the core of the Sun today, but it was low enough for the electromagnetic and weak forces to freeze out from the electroweak force. After this instant (10^{-10} second), all four forces were forever distinct in the universe.

The end of the electroweak era marked an important transition not only in the physical universe, but also in human understanding of the universe. The theory that unified the weak and electromagnetic forces, developed in the 1970s, predicted the emergence of new types of particles (called the W and Z bosons, or *weak bosons*) at temperatures above the 10^{15} K temperature of the universe when it was 10^{-10} second old. In 1983, experiments performed in a huge particle accelerator near the French/Swiss border (CERN) reached energies equivalent to such high temperatures for the first time. The new particles showed up just as predicted, produced from extremely high-energy particle collisions in accord with $E = mc^2$.

Thus, we have direct experimental evidence concerning the conditions in the universe at the end of the electroweak era. We do *not* have any direct experimental evidence of conditions prior to that time. Our theories concerning the earlier parts of the electroweak era and the GUT era consequently are much more speculative than our theories describing the universe from the end of the electroweak era to the present.

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

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

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

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

The Era of Nucleosynthesis So far, everything we have discussed occurred within the first 0.001 second of the universe's existence—a time span shorter than the time it takes you to blink an eye. At this point, the protons and neutrons left over after the annihilation of antimatter began to fuse into heavier nuclei. However, the heat of the universe remained so high that most nuclei broke apart as fast as they formed. This dance of fusion and breakup marked the **era of nucleosynthesis.**

The era of nucleosynthesis ended when the universe was about 3 minutes old. After this time, the density in the expanding universe had dropped so much that fusion no longer occurred, even though the temperature was still about a billion Kelvin (10^9 K)—much hotter than the temperature at the center of the Sun today. When fusion ceased, about 75% of the mass of the ordinary (baryonic) matter in the universe remained as individual protons, or hydrogen nuclei. The other 25% of this mass had fused into helium nuclei, with trace amounts of deuterium (hydrogen with a neutron) and lithium (the next heaviest element after hydrogen and helium). Except for the relatively small amount of matter that stars later forged into heavier elements, the chemical composition of the universe remains the same today.

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

The era of nuclei came to an end when the expanding universe was about 380,000 years old. At this point the temperature had fallen to about 3,000 K—roughly half the temperature of the Sun's surface today. Hydrogen and helium nuclei finally captured electrons for good, forming stable, neutral atoms for the first time. With electrons now bound into atoms, the universe suddenly became transparent, as if a thick fog had suddenly lifted. Photons, formerly trapped among the electrons, began to stream freely across the universe. We still see these photons today as the *cosmic microwave background*, which we will discuss shortly.

The Era of Atoms and the Era of Galaxies We've already discussed the rest of the story in earlier chapters of the book. The end of the era of nuclei marked the beginning of the **era of atoms,** when the universe consisted of a mixture of neutral atoms and plasma (ions and electrons), along with a large number of photons. Thanks to the slight density enhancements present in the universe at this time and the gravitational attraction of dark matter, the atoms and plasma slowly assembled into protogalactic clouds. Stars formed in these clouds, transforming the gas clouds into galaxies. The first full-fledged galaxies had formed by the time the universe was about 1 billion years old, beginning what we call the **era of galaxies.**

The era of galaxies continues to this day. Generation after generation of star formation in galaxies steadily builds elements heavier than helium and incorporates them into new star systems. Some of these star systems develop planets, and on at least one of these planets, life burst into being a few billion years ago. Now here we are, thinking about it all. Describing both the follies and the achievements of the human race, Carl Sagan once said, "These are the things that hydrogen atoms do—given 15 billion years of cosmic evolution." (Sagan died in 1996, before we refined the age of the universe to 14 billion years.)

23.2 Evidence for the Big Bang

Like any scientific theory, the Big Bang theory is a model of nature designed to explain a set of observations. If it is close to the truth, it should be able to make predictions about the real universe that we can verify through more observations

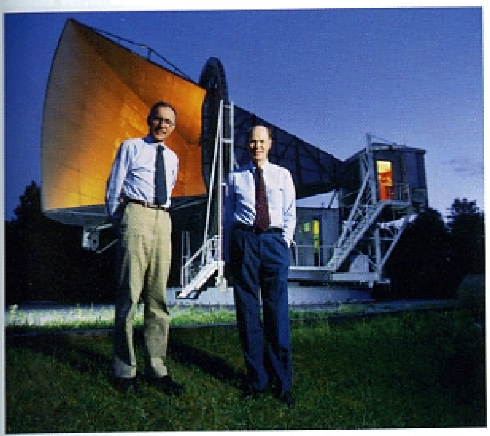


Figure 23.5 Arno Penzias and Robert Wilson, discoverers of the cosmic microwave background, with the Bell Labs microwave antenna.

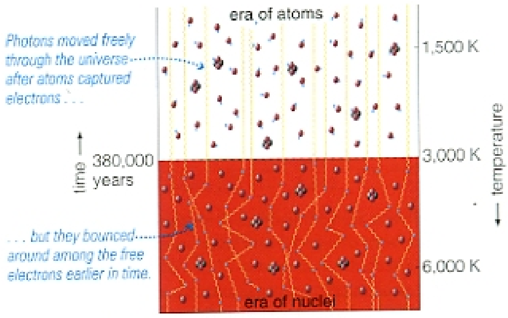


Figure 23.6 Interactive Figure Photons (yellow squiggles) frequently collided with free electrons during the era of nuclei and thus could travel freely only after electrons became bound into atoms. This transition was something like the transition from a dense fog to clear air. The photons released at the end of the era of nuclei, when the universe was about 380,000 years old, make up the cosmic microwave background. Precise measurements of these microwaves tell us what the universe was like at this moment in time.

or experiments. The Big Bang model has gained wide scientific acceptance for two key reasons:

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

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

• How do we observe the radiation left over from the Big Bang?

The first major piece of evidence supporting the Big Bang theory was announced in 1965. Arno Penzias and Robert Wilson, two physicists working at Bell Laboratories in New Jersey, were calibrating a sensitive microwave antenna designed for satellite communications (Figure 23.5). (*Microwaves* fall within the radio portion of the electromagnetic spectrum; see Figure 5.7.) Much to their chagrin, they kept finding unexpected "noise" in every measurement they made with the antenna.

Fearing that they were doing something wrong, Penzias and Wilson worked frantically to discover and eliminate all possible sources of background noise. They even climbed up on their antenna to scrape off pigeon droppings, on the off-chance that these were somehow causing the noise. No matter what they did, however, the microwave noise wouldn't go away. The noise was the same no matter where they pointed their antenna, indicating that it came from all directions in the sky and ruling out the possibility that it came from any particular astronomical object or from any place on Earth. Embarrassed by their inability to explain the noise, Penzias and Wilson prepared to "bury" their discovery about the noise at the end of a long scientific paper about their antenna.

Meanwhile, physicists at nearby Princeton University were busy calculating the expected characteristics of the radiation left over from the heat of the Big Bang. They concluded that, if the Big Bang had really occurred, this radiation should be permeating the entire universe and should be detectable with a microwave antenna. On a fateful airplane trip home from an astronomical meeting, Penzias sat next to an astronomer who told him of the Princeton calculations. The Princeton group soon met with Penzias and Wilson to compare notes. The "noise" in the Bell Labs antenna was not an embarrassment after all. Instead, it was the cosmic microwave background—and the first strong evidence that the Big Bang had really happened. Penzias and Wilson received the 1978 Nobel Prize in physics for their discovery of the cosmic microwave background.*

The cosmic microwave background consists of photons arriving at Earth directly from the end of the era of nuclei, when the universe was about 380,000 years old. Because neutral atoms finally could remain stable, they captured most of the electrons in the universe. With no more free electrons to block them, the photons from that epoch have flown unobstructed through the universe ever since (Figure 23.6). Thus, when we observe the cosmic microwave background, we essentially are seeing back to a time when the universe

*The dramatic story of the discovery of the cosmic microwave background is told in greater detail, along with much more scientific history, in Timothy Ferris, *The Red Limit* (New York: Quill, 1983). The possible existence of microwave radiation left over from the Big Bang was first predicted by George Gamow and his colleagues in the late 1940s, but neither Penzias and Wilson nor the Princeton group were aware of his work.

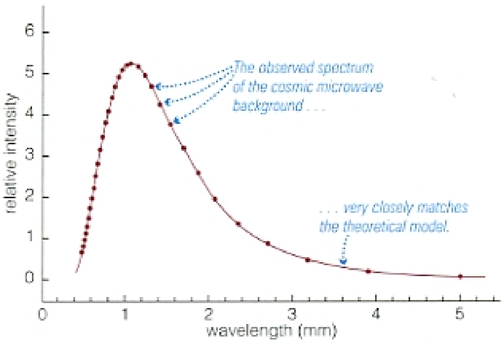


Figure 23.7 This graph shows the spectrum of the cosmic microwave background recorded by NASA's *COBE* satellite. A theoretically calculated thermal radiation spectrum (smooth curve) for a temperature of 2.73 K perfectly fits the data (dots). This excellent fit is important evidence in favor of the Big Bang theory.

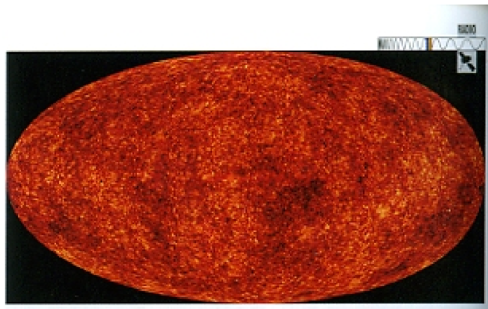


Figure 23.8 Interactive Photo This all-sky map shows temperature differences in the cosmic microwave background measured by *WMAP*. The background temperature is about 2.73 K everywhere, but the brightest regions of this picture are about 0.0001 K hotter than the darkest regions—indicating that the early universe was very slightly lumpy at the end of the era of nuclei. We are essentially seeing what the universe was like at the surface marked "380,000 years" in Figure 23.3. Gravity later drew matter toward the centers of these lumps, forming the structures we see in the universe today.

was only 380,000 years old. In that sense, we are seeing light from the most distant regions of the observable universe—only 380,000 light-years from our cosmological horizon [Section 20.3].

Surprisingly, it does not take a particularly powerful telescope to "see" this radiation. In fact, you can pick it up with an ordinary television antenna. If you set an antenna-fed television (that is, *not* cable or satellite TV) to a channel for which there is no local station, you will see a screen full of static "snow." About 1% of this static is due to photons in the cosmic microwave background. Try it. If your friends ask why you are watching nothing, tell them that you are actually watching the most incredible sight ever seen on a television screen: the Big Bang, or at least as close to it as we'll ever get.

The cosmic microwave background came from the heat of the universe itself and therefore should have an essentially perfect thermal radiation spectrum [Section 5.4]. When this radiation first broke free 380,000 years after the Big Bang, the temperature of the universe was about 3,000 K, not too different from that of a red giant star's surface. Thus, the spectrum of the cosmic microwave background originally peaked in visible light, just like the thermal radiation from a red star, with wavelengths of a few hundred nanometers. However, the universe has expanded by a factor of about 1,000 since that time, stretching the wavelengths of these photons by the same amount [Section 20.3]. Their wavelengths have therefore shifted to about a millimeter, squarely in the microwave portion of the spectrum and corresponding to a temperature of a few degrees above absolute zero.

In the early 1990s, a NASA satellite called the *Cosmic Background Explorer (COBE)* was launched to test these ideas about the cosmic microwave background. The results were a stunning success for the Big Bang theory. As shown in Figure 23.7, the cosmic microwave background does indeed have a perfect thermal radiation spectrum, with a peak corresponding to a temperature of 2.73 K. In a very real sense, the temperature of the night sky is a frigid 3 degrees above absolute zero.

THINK ABOUT IT

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

COBE achieved an even greater success mapping the temperature of the cosmic microwave background in all directions. It was already known that the cosmic microwave background is extraordinarily uniform throughout the universe. Conditions in the early universe must have been extremely uniform to produce such a smooth radiation field. For a time, this uniformity was considered a strike against the Big Bang theory because, as we discussed in Chapters 21 and 22, the universe must have contained some regions of enhanced density in order to explain the formation of galaxies. The *COBE* measurements restored confidence in the Big Bang theory because they showed that the cosmic microwave background is *not quite* perfectly uniform. Instead, its temperature varies very slightly from one place to another by a few parts in 100,000.*

More recently, NASA's *Wilkinson Microwave Anisotropy Probe (WMAP)* has provided even more dramatic confirmation of the small temperature variations, with a map of the cosmic microwave background released in 2003 (Figure 23.8). These variations in temperature indicate that the density of the early universe really did differ slightly from

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

MATHEMATICAL INSIGHT 23.1 Temperature and Wavelength of Background Radiation

As shown in Figure 23.7, the spectrum of the cosmic microwave background is a nearly perfect thermal radiation spectrum for an object at a temperature of 2.73 K. Thus, we infer that the current temperature of the universe itself is a little less than 3 K. We can calculate the wavelength of the photons at the peak of the spectrum using Wien's law, which we discussed in Mathematical Insight 5.2:

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

If you remember that 10^6 nm = 1 mm, then you'll see that this value is equivalent to 1.1 millimeters. In other words, the spectrum of the cosmic microwave background currently peaks at a wavelength of about 1 millimeter (notice that this agrees with Figure 23.7). But what was the wavelength of the cosmic microwave photons in the past?

Remember that the expansion of the universe stretches the photons within it, changing their wavelengths through the effect we call the *cosmological redshift* [Section 20.3]. From Mathematical Insight 20.5, we know that the universe has grown in size by a factor of $(1 + z)$ since the time light left objects that we observe to have a redshift z. Thus, to find the peak wavelength of photons in the cosmic microwave background at any past time in terms of the redshift z, we simply need to divide the current peak wavelength by $(1 + z)$:

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

Because higher values of z correspond to earlier times in the history of the universe, this formula tells us that the peak wavelength of the background radiation was *shorter* at earlier moments in time. Moreover, for a thermal radiation spectrum, a shorter peak wavelength means a *higher* temperature. Combining our result for the peak wavelength at redshift z with Wien's law, we find a simple formula for the temperature of the universe at any earlier time at which we see objects with redshift z:

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

Notice that, as we expect, this formula will give a higher temperature at times in the past that correspond to higher redshift z.

Example 1: What was peak wavelength of the photons in background radiation of the universe at the time they began to travel freely through the universe? Assume that the temperature of the universe at this time was 3,000 K.

Solution:

Step 1 Understand: We are given the temperature of the universe and are asked to find the peak wavelength of the thermal radiation corresponding to that temperature. We therefore need to use Wien's law relating peak wavelength to temperature.

Step 2 Solve: We plug the temperature of 3,000 K into Wien's law:

$$\lambda_{max} \approx \frac{2{,}900{,}000}{T(\text{Kelvin})} \text{nm} = \frac{2{,}900{,}000}{3{,}000} \text{nm} = 970 \text{ nm}$$

Step 3 Explain: We have found that the peak wavelength of the background radiation at the time it began to travel freely through the universe was about 970 nanometers, which is in the infrared portion of the electromagnetic spectrum fairly close to the wavelength of red visible light (see Figure 5.7). This fact should not be surprising, because 3,000 K is roughly the same temperature as the surface of a red giant. In other words, the entire universe at the time would have been filled with light as bright as you would see if you were just beneath the surface of a red giant star.

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

Solution:

Step 1 Understand: One way to answer this question would be to use Wien's law to calculate the wavelength of the background radiation both now and when the universe was at a temperature of 3,000 K and compare the results. However, an easier way is to use the formula we found above that relates the temperature of the background radiation to the cosmological redshift z. We are given the 3,000 K temperature, so we simply need to find the stretching factor $(1 + z)$.

Step 2 Solve: We solve the formula found above for the factor $(1 + z)$ by dividing both sides of the equation by the current temperature of the universe, 2.73 K; you should confirm that the formula becomes:

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

In this case, we are looking for the stretching factor corresponding to the time when the universe had a temperature of 3,000 K. Plugging this value into the formula, we find:

$$1 + z = \frac{3{,}000 \text{ K}}{2.73 \text{ K}} \approx 1{,}100$$

Step 3 Explain: We have found that the expansion of the universe has stretched photons by a factor of about 1,000 since the time they first began to travel freely across the universe, when the universe was about 380,000 years old. Notice that the answer has no units because it tells us the *ratio* of the size of the universe now to the size of the universe then.

SPECIAL TOPIC The Steady State Universe

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

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

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place to place. The seeds of structure formation were indeed present during the era of nuclei.

The discovery of density enhancements bolstered the idea that some of the dark matter consists of WIMPs that we have not yet identified [Section 22.2] and that the gravity of this dark matter drove the formation of structure in the universe. Regions of enhanced density can grow into galaxies because the extra gravity in these regions draws matter together even while the rest of the universe expands. The greater the density enhancements, the faster matter should have collected into galaxies.

Detailed calculations show that, to explain the fact that galaxies formed within a few billion years, the density enhancements at the end of the era of nuclei must have been significantly greater than the few parts in 100,000 suggested by the temperature variations in the cosmic microwave background. Because WIMPs are weakly interacting and do not interact with photons, we do not expect them to influence the temperature of the cosmic microwave background directly. However, the gravity of the WIMPs can collect ordinary baryonic matter into clumps that *do* interact with photons. Thus, the small density enhancements detected by microwave telescopes appear to echo much larger density enhancements made up of WIMPs. Careful modeling of these temperature variations shows that they are consistent with dark-matter density enhancements large enough to account for the structure we see in the universe today.

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

The discovery of the cosmic microwave background in 1965 quickly solved another long-standing astronomical problem: the origin of cosmic helium. Everywhere in the universe, about one-quarter of the mass of ordinary matter (not including dark matter) is helium. The Milky Way's helium fraction is about 28%, and no galaxy has a helium fraction lower than 25%. A small proportion of this helium comes from hydrogen fusion in stars, but most does not: Fusion of hydrogen to helium in stars could have produced only about 10% of the observed helium.

The majority of the helium in the universe must already have been present in the protogalactic clouds that preceded the formation of galaxies. In other words, the universe itself must once have been hot enough to fuse hydrogen into helium. The current microwave background temperature of 2.73 K tells us precisely how hot the universe was in the distant past and exactly how much helium it should have made. The result—25% helium—is another impressive success of the Big Bang theory.

Helium Formation in the Early Universe In order to see why 25% of ordinary matter became helium, we need to understand what protons and neutrons were doing during the 3 minutes that marked the era of nucleosynthesis. Early in this era, when the universe's temperature was 10^{11} K, nuclear reactions could convert protons into neutrons, and vice versa. As long as the universe remained hotter than 10^{11} K, these reactions kept the numbers of protons and neutrons nearly equal. But as the universe cooled, neutron-proton conversion reactions began to favor protons.

Neutrons are slightly more massive than protons, and therefore reactions that convert protons to neutrons require energy to proceed (in accordance with $E = mc^2$). As the temperature fell below 10^{11} K, the required energy for neutron production was no longer readily available, so the rate of these reactions slowed. In contrast, reactions that convert neutrons into protons release energy and thus are unhindered by cooler temperatures. By the time the temperature of the universe fell to 10^{10} K, protons began to outnumber neutrons because the conversion reactions ran in only one direction. Neutrons changed into protons, but the protons didn't change back.

For about the next 3 minutes, the universe was still hot and dense enough for nuclear fusion to operate. Protons and neutrons constantly combined to form *deuterium*—the rare form of hydrogen nuclei that contains a neutron in addition to a proton—and deuterium nuclei fused to form helium (Figure 23.9). However, during the early part of the era of nucleosynthesis, the helium nuclei were almost immediately blasted apart by one of the many gamma rays that filled the universe.

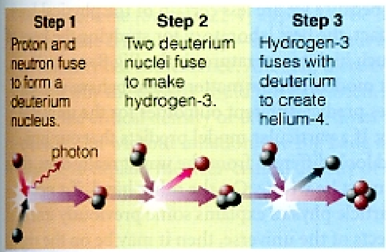


Figure 23.9 During the 3-minute-long era of nucleosynthesis, virtually all the neutrons in the universe fused with protons to form helium-4. This figure illustrates one of several possible reaction pathways.

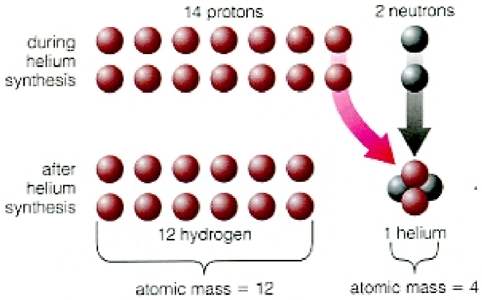


Figure 23.10 Calculations show that protons outnumbered neutrons 7 to 1, which is the same as 14 to 2, during the era of nucleosynthesis. The result was 12 hydrogen nuclei (individual protons) for each helium nucleus. Thus, the hydrogen-to-helium mass ratio is 12 to 4, which is the same as 75% to 25%. The agreement between this prediction and the observed abundance of helium is important evidence in favor of the Big Bang theory.

Fusion began to create long-lasting helium nuclei when the universe was about 1 minute old and had cooled to a temperature at which it contained few destructive gamma rays. Calculations show that the proton-to-neutron ratio at this time should have been about 7 to 1. Moreover, almost all the available neutrons should have become incorporated into nuclei of helium-4. Figure 23.10 shows that, based on the 7-to-1 ratio of protons to neutrons, the universe should have had a composition of 75% hydrogen and 25% helium by mass at the end of the era of nucleosynthesis.

Thus, the Big Bang theory makes a very concrete prediction about the chemical composition of the universe: It should be 75% hydrogen and 25% helium by mass. The fact that observations confirm this predicted ratio of hydrogen to helium is another striking success of the Big Bang theory.

THINK ABOUT IT

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

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

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

The Density of Ordinary Matter Calculations made with the Big Bang model allow scientists to estimate the density of ordinary (baryonic) matter in the universe from the observed amount of deuterium in the universe today. Remember that, during the era of nucleosynthesis, protons and neutrons first fused into deuterium and the deuterium nuclei then fused into helium. The fact that some deuterium nuclei still exist in the universe indicates that this process stopped before all the deuterium nuclei were used up. The amount of deuterium in the universe today therefore tells us about the density of protons and neutrons (baryons) during the era of nucleosynthesis: The higher the density, the more efficiently fusion would have proceeded. Thus, a higher density in the early universe would have left less deuterium in the universe today, and a lower density would have left more deuterium.

Observations show that about one out of every 40,000 hydrogen atoms contains a deuterium nucleus—that is, a nucleus with a neutron in addition to its proton. Calculations based on this deuterium abundance show that the density of ordinary (baryonic) matter in the universe is about 4% of the critical density (Figure 23.11). (Recall that the critical density is the density required if the expansion of the universe is to stop and reverse someday [Section 22.4].) Similar calculations based on the observed abundance of lithium and helium-3 lead to the same conclusion, adding to our confidence in the Big Bang model.

These results also lead to an astonishing prediction about the nature of dark matter. Recall that the overall density

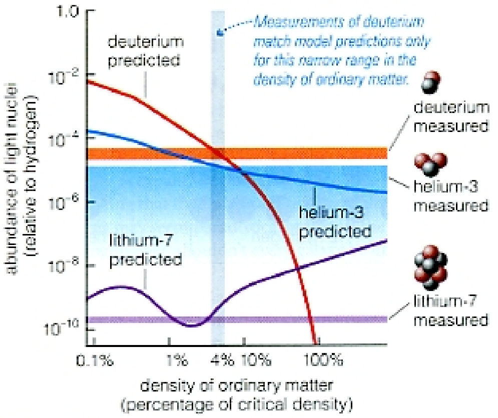


Figure 23.11 This graph shows how the measured abundances of deuterium, helium-3, and lithium-7 lead to the conclusion that the density of ordinary matter is about 4% of the critical density. The three horizontal swaths show measured abundances; the thickness of each swath represents the range of uncertainty in the measurements. (The upper edge of the blue swath indicates the upper limit on the helium-3 abundance; a lower limit has not yet been established.) The three curves represent models based on the Big Bang theory; these curves show how the abundance of each type of nucleus is expected to depend on the density of ordinary matter in the universe. Notice that the predictions (curves) match up with the measurements (horizontal swaths) only in the gray vertical strip, which represents a density of about 4% of the critical density.

of the universe appears to be close to 25% of the critical density [Section 22.4]. Because this is about six times as large as the 4% of critical density that we find for ordinary matter, we conclude that the universe contains about six times as much extraordinary (nonbaryonic) dark matter as it does of ordinary (baryonic) matter. Unless we are missing something fundamental in our understanding of all these issues, the Big Bang model predicts that extraordinary (nonbaryonic) dark matter such as WIMPs constitutes the majority of the universe's mass. That is why most astronomers think that dark matter consists mostly of WIMPs, and why many scientists are actively trying to find ways to detect WIMPs and learn about their properties.

THINK ABOUT IT

The ideas just discussed point to a rather amazing fact: Although we have yet to discover any WIMPs, we suspect they dominate the total mass of the universe. Briefly explain how this is possible, and comment on how confident we can be that weakly interacting particles make up the bulk of dark matter.

23.3 The Big Bang and Inflation

The Big Bang model relies heavily on our knowledge of particle physics, which has been tested to temperatures of 10^{15} K, corresponding to temperatures at the end of the electroweak era, when the universe was a mere 10^{-10} second old. Our knowledge of earlier times rests on a weaker foundation because we are less certain of the physical laws at work. In fact, the best laboratory for studying the laws of physics at such high temperatures is the Big Bang itself.

Different models of how matter might behave at such high energies predict different outcomes for the universe we see today. If a particular model predicts that our universe should look different from the way it really does, then that model must be wrong. On the other hand, if a new model of particle physics explains some previously unexplained aspects of the universe, then it may be on the right track. The grand unified theories of particle physics discussed in Section 23.1 have not yet been extensively tested, but many scientists believe that these theories are on the right track for just this reason. In particular, the grand unified theories suggest that the universe at a very early age underwent the dramatic burst of expansion that we call *inflation*, and inflation seems to explain several key aspects of our universe that are otherwise left unexplained by the Big Bang theory.

• What aspects of the universe were originally unexplained by the Big Bang model?

The Big Bang theory has gained wide acceptance because of the strong evidence from the cosmic microwave background and the measured abundances of light elements in the universe. However, without the addition of more speculative physics such as that of the grand unified theories and their prediction of inflation, the Big Bang theory leaves several major aspects of our universe unexplained. Three of the most pressing questions are the following:

- *Where does structure come from?* Recall that our models of the formation of galaxies and larger structures all assume that gravity collected matter around regions of slightly enhanced density in the early universe. Thus, explaining the origin of structure requires that the Big Bang must have somehow produced these slight density enhancements. The subtle temperature differences seen in the cosmic microwave background (see Figure 23.8) tell us that regions of enhanced density did indeed exist at the end of the era of nuclei, when the universe was 380,000 years old. But we still need to explain where the density enhancements came from.
- *Why is the large-scale universe so uniform?* Although the slight temperature variations in the cosmic microwave background show that the universe is not *perfectly* uniform on large scales, the overall smoothness is nonetheless remarkable. Observations of the cosmic microwave background tell us that the density of the universe at the end of the era of nuclei varied from place to place by no more than about 0.01%, and this uniformity explains why distant reaches of the universe look so similar today. Without inflation, the Big Bang theory does not explain why distant reaches of the universe look so similar.
- *Why is the density of the universe close to the critical density?* The total density of dark matter plus dark energy

in the universe [Section 22.4] appears to be remarkably close to the critical density—so close that it is difficult to consider it a coincidence. After all, there is no obvious reason why the density could not have been, say, 1,000 times the critical density or 0.0000001 times the critical density. But without inflation, the Big Bang model is unable to explain the near-critical density of the universe as anything other than luck.

• How does inflation explain these features of the universe?

Physicist Alan Guth realized in 1981 that grand unified theories could potentially answer all three questions. These theories predict that the separation of the strong force from the GUT force should have released enormous energy, causing the universe to expand dramatically, perhaps by a factor of 10^{30} in less than 10^{-36} second. This dramatic expansion is what we call *inflation*. While it sounds outrageous to talk about something that happened in the first trillion-trillion-trillionth of a second in the history of the universe, inflation may have shaped the way the universe looks today.

Structure: Giant Quantum Fluctuations To understand how inflation explains the origin of structure, we need to recognize a special feature of energy fields. Laboratory-tested principles of quantum mechanics, especially the uncertainty principle [Section S4.3], tell us that on very small scales, the energy fields at any point in space are always fluctuating. Thus, the distribution of energy through space is very slightly irregular, even in a complete vacuum. The tiny quantum "ripples" that make up the irregularities can be characterized by a wavelength that corresponds roughly to their size. In principle, quantum ripples in the very early universe could have been the seeds for density enhancements that later grew into galaxies. However, the wavelengths of the original ripples were far too small to explain density enhancements like those we see imprinted on the cosmic microwave background.

Inflation would have dramatically increased the wavelengths of these quantum fluctuations. The fantastic growth of the universe during the period of inflation would have stretched tiny ripples from a size smaller than an atomic nucleus to the size of our solar system (Figure 23.12), making them large enough to become the density enhancements from which galaxies and larger structures later formed. Amazingly, the structure of today's universe may have started as tiny quantum fluctuations just before the period of inflation.

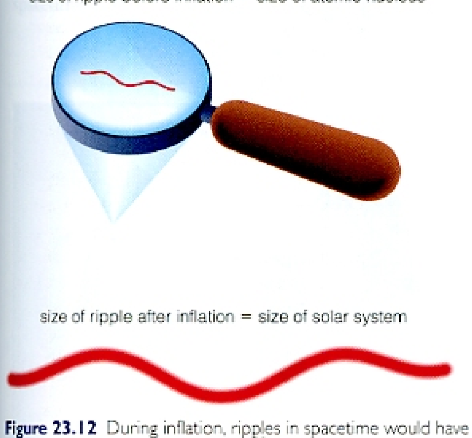


Figure 23.12 During inflation, ripples in spacetime would have stretched by a factor of perhaps 10^{30}. The peaks of these ripples then would have become the density enhancements that produced all the structure we see in the universe today.

Uniformity: Equalizing Temperatures and Densities We'll next consider how inflation explains the overall uniformity of the universe on large scales, but first let's look more closely at the question of why the uniformity is surprising. The idea that different parts of the universe were very similar shortly after the Big Bang may seem quite natural, but on further inspection the uniformity of the universe becomes difficult to explain.

Imagine observing the cosmic microwave background in a certain part of the sky. You are seeing microwaves that have traveled through the universe since the end of the era of nuclei, just 380,000 years after the Big Bang. Thus, you are seeing a region of the universe as it was some 14 billion years ago, when the universe was only 380,000 years old. Now imagine turning around and looking at the background radiation coming from the opposite direction. You are also seeing this region at an age of 380,000 years, and it looks virtually identical in temperature and density. The surprising part is this: The two regions are billions of light-years apart on opposite sides of our observable universe but we are seeing them as they were when they were only 380,000 years old. They can't possibly have exchanged light or any other information (Figure 23.13). A signal traveling at the speed of light from one to the other would barely have started

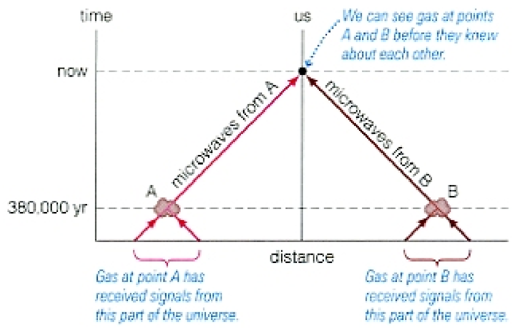


Figure 23.13 Light left the microwave-emitting regions we see on opposite sides of the universe long before they could have communicated with each other and equalized their temperatures, yet their temperatures are virtually identical. Without inflation these similar temperatures are a puzzle.

its journey. So how did they come to have the same temperature and density?

Inflation answers this question by saying that even though the two regions cannot have had any contact *since* the time of inflation, they were in contact prior to that time. Before the onset of inflation, when the universe was 10^{-38} second old, the two regions were less than 10^{-38} light-second away from one another. Thus, radiation traveling at the speed of light would have had time to bounce between the two regions, and this exchange of energy equalized their temperatures and densities. Inflation then pushed these equalized regions to much greater distances, far out of contact with one another (Figure 23.14). Like criminals getting their stories straight before being locked in separate jail cells, the two regions (and all other parts of the observable universe) came to the same temperature and density before inflation spread them far apart.

Because inflation caused different regions of the universe to separate so vastly in such a short period of time, many people wonder whether inflation violates Einstein's theories, saying that nothing can move faster than the speed of light. It does not, because nothing actually *moves* through space as a result of inflation or the ongoing expansion of the universe. Instead, the expansion of the universe is the expansion of *space itself.* Objects may be separating from one another at a speed faster than the speed of light, but no matter or radiation is able to travel between them during that time. In essence, inflation opens up a huge gap in space between objects that were once close together. The objects get very far apart, but nothing ever travels between them at a speed that exceeds the speed of light.

Density: Balancing the Universe The third question answered by inflation asks why the matter density of the universe is

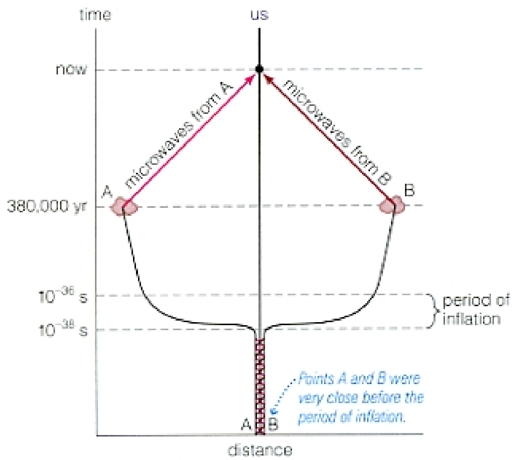


Figure 23.14 Interactive figure Before inflation, regions A and B were near enough to communicate and equalize their temperatures. Inflation then pushed them far apart. Today, we can see both A and B, but they are too far apart to see each other.

so close to the critical density. Another way to say that the universe's density is close to critical is to say that the overall geometry of the universe is remarkably "flat." To understand this idea, we must consider the overall geometry of the universe in a little more detail.

Recall that Einstein's general theory of relativity tells us that the presence of matter can curve the structure of spacetime [Section S3.3]. Although we cannot visualize this curvature in all three dimensions of space (or all four dimensions of spacetime), we can detect its presence by its effects on light. For example, observations of gravitational lensing [Section 22.2] tell us that we are seeing light that has passed through a curved region of space. Although the curvature of the universe can vary from place to place, the universe as a whole must have some overall shape. Almost any shape is possible, but all the possibilities fall into just three general categories (Figure 23.15). By analogy to objects that we can see in three dimensions, scientists refer to these three categories of shape as *flat* (or critical), *spherical* (or closed), and *saddle shaped* (or open).

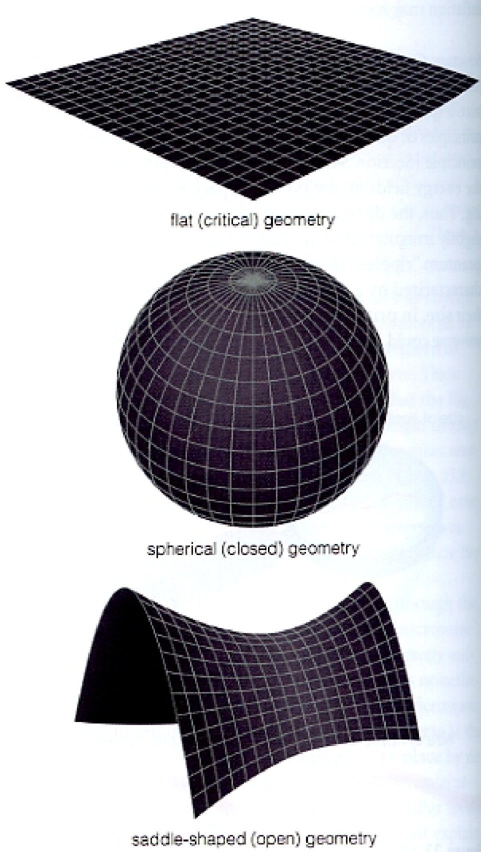


Figure 23.15 Analogies to the three possible categories of overall geometry for the universe. Keep in mind that the real universe has these "shapes" in more dimensions than we can see.

According to general relativity, the overall geometry would be flat if the matter density of the universe were precisely equal to the critical density, in which case the kinetic energy of expansion would precisely balance the universe's overall gravitational pull. In the absence of dark energy, any imbalance in these energies causes curvature of spacetime, and deviations from precise balance grow more severe as the universe evolves. For example, if the universe had been 10% denser at the end of the era of nuclei, it would have collapsed long ago. On the other hand, if it had been 10% less dense at that time, galaxies would never have formed before expansion spread all the matter too thin. Thus, the universe had to start out remarkably balanced to be even remotely close to flat today.

Inflation can explain this precise balance by its effects on the geometry of the universe. In terms of Einstein's theory, the effect of inflation on spacetime curvature is similar to the flattening of a balloon's surface when you blow into it (Figure 23.16). The flattening of space during the period of inflation would have been so enormous that any curvature the universe might have had previously would be noticeable only on size scales much larger than the observable universe. Thus, inflation predicts that the overall geometry of the universe should appear perfectly flat, in which case the overall density of matter plus energy should be precisely equal to the critical density.

The fine balance predicted by inflation turns out to be both a success and a potential pitfall of the inflation theory. On one hand, it explains how the universe managed to have a density just right to allow the birth of galaxies. On the other hand, its prediction of a perfectly flat universe seems to disagree with observations showing that the total density of matter (including dark matter) is only about 25% of the critical density.

Dark energy might explain this shortfall in the density of dark matter. Remember that Einstein's theory of relativity tells us that mass can be transformed into energy and vice versa, which means that energy must be able to curve spacetime in the same way that mass can curve spacetime

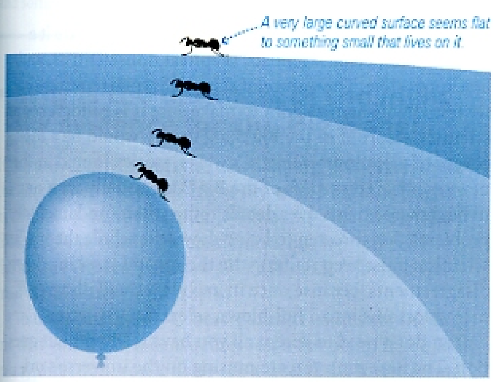


Figure 23.16 As a balloon expands, its surface seems increasingly flat to an ant crawling along it. Inflation is thought to have made the universe seem flat in a similar way.

[Section S3.3]. Thus, the dark energy associated with a large-scale repulsive force could compensate for the shortfall in the matter density, making the present-day universe flatter than it would otherwise be. Remarkably, the supernova measurements indicating that the expansion of the universe is accelerating [Section 22.4] also show that the strength of the implied repulsive force is about right to render the universe perfectly flat, just as inflation predicts. In other words, the total density of matter and dark energy together may indeed be precisely equal to the critical density.

• How can we test the idea of inflation?

We've seen that inflation answers some outstanding mysteries about the universe, but did it really happen? We cannot directly observe the universe at the very early time when inflation is thought to have occurred. Nevertheless, we can test the idea of inflation by exploring whether its predictions are consistent with our observations of the universe at later times. Scientists are only beginning to make observations that test inflation, but the findings to date are consistent with the idea that an early inflationary episode made the universe uniform and flat while planting the seeds of structure formation.

The strongest tests of inflation to date come from detailed studies of the cosmic microwave background, and in particular of the map made by the *WMAP* satellite (see Figure 23.8). Remember that this map shows tiny temperature differences corresponding to density variations in the universe at the end of the era of nuclei, when the universe was about 380,000 years old. However, according to the idea of inflation, these density enhancements were actually created much earlier, when inflation caused tiny quantum ripples to expand into seeds of structure. Thus, careful observations of the temperature variations in the microwave background can tell us about the structure of the universe during its first instant of existence.

For example, complex calculations show that the largest temperature differences in the cosmic microwave background should typically be between patches of sky separated by about 1° if the overall geometry of the universe is flat. (Similar calculations show that this angular separation would be smaller than 1° if the universe were open and curved like a saddle, and larger than 1° if the universe were closed and curved like a sphere [Section 22.4].) The strongest temperature differences are indeed observed at angular separations of 1°, indicating that the universe is geometrically flat, as predicted by inflation.

In fact, the overall pattern of temperature differences agrees with the predictions of models based on inflation, which is why these results tend to support the idea that inflation really occurred. Figure 23.17 shows an analysis of the temperature variations observed by *WMAP* in the cosmic microwave background, along with additional data from other microwave telescopes. The graph shows how the typical temperature differences between patches of sky depend on their angular size on the celestial sphere. The

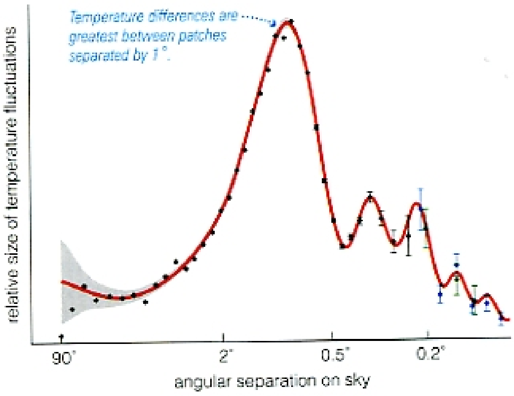


Figure 23.17 This graph shows how detailed analysis of temperature differences in the cosmic microwave background supports the idea of inflation. The data points indicate how the typical temperature differences between patches of sky depend on their angular size on the celestial sphere. (Black dots come from the *WMAP* data shown in Figure 23.8, and the blue and green points represent data from other telescopes.) The red curve shows the prediction of a model that relies on inflation to produce a universe whose ordinary matter density, dark-matter density, and expansion rate are all similar to their observed values. Close agreement between the data points and the model indicates that the universe we live in has many of the characteristics predicted by that model.

dots represent data from the observations, and the red curve shows the inflation-based model that best fits the observations. This model makes specific predictions not only about the data shown in the figure, but also about other characteristics of our universe such as its overall geometry, composition, and age. Thus, in a sense, these new observations of the cosmic microwave background are revealing the characteristics of the seeds from which our universe has grown. To the extent that we have been able to observe those seeds, their nature aligns reassuringly well with the universe we observe about us at the present time. According to the model shown in the figure, today's universe should have the following features:

- The overall geometry is flat, implying that the total mass-energy of the universe must be equivalent to the critical density.
- The density of ordinary (baryonic) matter is 4.4% of the critical density, in agreement with observations of deuterium in the universe [Section 23.2].
- The total matter density is 27% of the critical density. Subtracting the 4.4% for ordinary matter, we conclude that extraordinary (nonbaryonic) dark matter makes up about 23% of the critical density, in agreement with what we infer from measurements of the masses of clusters of galaxies [Section 22.4].
- The combination of a flat geometry and a matter density lower than the critical density implies the existence of a repulsive "dark energy" that currently accelerates the expansion, in agreement with observations of distant supernovae [Section 22.4]. Because the total mass-energy of the universe is the critical density, and matter accounts for only 27% of this, dark energy must account for the remaining 73% of the mass-energy of the universe.
- The universe's age should be about 13.7 billion years at the current microwave temperature of 2.73 K, in agreement with what we infer from Hubble's constant [Section 20.3] and the ages of the oldest stars [Section 15.3].

This close correspondence between the seeds inherent in the universe at an age of 380,000 years and our observations of the present-day universe, some 14 billion years later, is persuasive evidence in favor of the Big Bang in general and inflation in particular. The bottom line is that, all things considered, inflation does a remarkable job of explaining features of our universe that are otherwise unaccounted for in the Big Bang theory. Many astronomers and physicists therefore suspect that some process akin to inflation did affect the early universe, but the details of the interaction between high-energy particle physics and the evolving universe remain unclear. If these details can be worked out successfully, we face an amazing prospect—a breakthrough in our understanding of the very smallest particles, achieved by studying the universe on the largest observable scales.

23.4 Observing the Big Bang for Yourself

You might occasionally read an article in a newspaper or a magazine questioning whether the Big Bang really happened. We will never be able to prove with absolute certainty that the Big Bang theory is correct. However, no one has come up with any other model of the universe that so successfully explains so much of what we see. As we have discussed, the Big Bang model makes at least two specific predictions that we have observationally verified: the characteristics of the cosmic microwave background and the composition of the universe. It also explains quite naturally many other features of the universe. So far, at least, we know of nothing that is inconsistent with the Big Bang model.

The Big Bang theory's very success has also made it a target for respected scientists, skeptical nonscientists, and crackpots alike. The nature of scientific work requires that we test established wisdom to make sure it is valid. A sound scientific disproof of the Big Bang theory would be a discovery of great importance. However, stories touted in the news media as disproofs of the Big Bang usually turn out to be disagreements over details rather than fundamental problems that threaten to bring down the whole theory. Yet scientists must keep refining the theory and tracking down disagreements, because once in a while a small disagreement blossoms into a full-blown scientific revolution.

You don't need to accept all you have read without question. The next time you are musing on the universe's origins, try an experiment for yourself. Go outside on a clear night, look at the sky, and ask yourself why it is dark.

SPECIAL TOPIC How Will the Universe End?

According to the Big Bang theory, time and space have a beginning in the Big Bang. Do they also have an end? If we live in a recollapsing universe [Section 22.4], the answer seems to be a clear "yes." Sometime in the distant future, the universal expansion will cease and reverse, and the universe will eventually come to an end in a fiery "Big Crunch." However, it now appears unlikely that we live in a recollapsing universe, in which case the universe seems destined to expand forever.

If dark energy is real, our Local Group of galaxies will become increasingly more lonely as the acceleration of the universe carries the more distant galaxies ever faster away from us. Some scientists speculated that the repulsive force of dark energy might even strengthen with time. In that case, the galaxies of the Local Group will someday separate, and the growing repulsive force could eventually tear apart our galaxy, our solar system, and even matter itself in a catastrophic event sometimes called the "Big Rip." However, the Big Rip is quite speculative; a more plausible scenario for the end of a perpetually expanding universe proceeds as follows.

The star-gas-star cycle in galaxies cannot continue forever, because not all the material is recycled. With each generation of stars, more mass becomes locked up in planets, brown dwarfs, white dwarfs, neutron stars, and black holes. Eventually, about a trillion years from now, even the longest-lived stars will burn out, and the galaxies will fade into darkness.

At this point, the only new action in the universe will occur on the rare occasions when two objects—such as two brown dwarfs or two white dwarfs—collide within a galaxy. The vast distances separating star systems in galaxies make such collisions extremely rare. For example, the probability of our Sun (or the white dwarf that it will become) colliding with another star is so small that it would be expected to happen only once in a quadrillion (10^{15}) years. Forever is a long time, however, and even low-probability events will eventually happen many times. If a star system experiences a collision once in a quadrillion years, it will experience about 100 collisions in 100 quadrillion (10^{17}) years. By the time the universe reaches an age of 10^{20} years, star systems will have suffered an average of 100,000 collisions each, making a time-lapse history of any galaxy look like a cosmic game of pinball.

These multiple collisions will severely disrupt galaxies. As in any gravitational encounter, some objects lose energy in such collisions and some gain energy. Objects that gain enough energy will be flung into intergalactic space, where they will drift ever farther from all other objects with the expansion of the universe. Objects that lose energy will eventually fall to the galactic center and will enter the black hole that sits there, adding to its mass and ultimately creating a gigantic black hole where our galaxy used to be. The remains of the universe will consist of black holes with masses as great as a trillion solar masses that are widely separated from a few scattered planets, brown dwarfs, and stellar corpses. If Earth somehow survives, it will be a frozen chunk of rock in the darkness of the expanding universe, billions of light-years from any other solid object.

If grand unified theories are correct, Earth still cannot last forever. These theories predict that protons will eventually fall apart. The predicted lifetime of protons is extremely long: a half-life of at least 10^{33} years. However, if protons really do decay, then by the time the universe is 10^{40} years old, Earth and all other atomic matter will have disintegrated into radiation and subatomic particles such as electrons and neutrinos.

The final phase may come through a mechanism proposed by Stephen Hawking. According to Hawking's theory, even black holes cannot last forever. Instead, they slowly "evaporate," their mass-energy turning into radiation. The process is so slow that we do not expect to be able to see it from any existing black holes, but if Hawking is correct, then black holes in the distant future will disappear in brilliant bursts of radiation. The largest black holes last longest, but even trillion-solar-mass black holes will evaporate sometime after the universe reaches an age of 10^{100} years. From then on, the universe will consist only of individual photons and subatomic particles, each separated by enormous distances from the others. Nothing new will ever happen, and no events will ever occur that would allow an omniscient observer to distinguish past from future. In a sense, the universe will finally have reached the end of time.

Lest any of this sound depressing, keep in mind that 10^{100} years is an indescribably long time. As an example, imagine that you wanted to write on a piece of paper a number that consisted of a 1 followed by 10^{100} zeros (that is, the number $10^{10^{100}}$). It sounds easy, but a piece of paper large enough to hold all those zeros *would not fit in the observable universe* today. If that still does not alleviate your concerns, you may be glad to know that a few creative thinkers speculate about ways in which the universe might undergo rebirth, even after the end of time.

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

If the universe were infinite, unchanging, and everywhere the same, then the entire night sky would blaze as brightly as the Sun. Johannes Kepler [Section 3.3] was one of the first people to reach this conclusion, but we now refer to the idea as **Olbers' paradox** after Heinrich Olbers, a German astronomer of the 1800s.

To understand how Olbers' paradox comes about, imagine that you are in a dense forest on a flat plain. If you look in any direction, you'll likely see a tree. If the forest is small, you might be able to see through some gaps in the trees to the open plains, but larger forests have fewer gaps (Figure 23.18). An infinite forest would have no gaps at all—a tree trunk would block your view along any line of sight.

The universe is like a forest of stars in this respect. In an unchanging universe with an infinite number of stars, we would see a star in every direction, making every point in the sky as bright as the Sun's surface. Even the presence of obscuring dust would not change this conclusion. The intense starlight would heat the dust over time until it too glowed like the Sun or evaporated away.

There are only two ways out of this dilemma. Either the universe has a finite number of stars, in which case we would not see a star in every direction, or it changes over time in some way that prevents us from seeing an infinite number of stars. For several centuries after Kepler first

a In a large forest, a tree will block your view no matter where you look. Similarly, in an unchanging universe with an infinite number of stars, we would expect to see stars in every direction, making the sky bright even at night.

b In a small forest with a smaller number of trees, you can see open spaces beyond the trees. Because the night sky is dark, the universe must similarly have spaces in which we see nothing beyond the stars, which means either that the number of stars is finite or that the universe changes in a way that prevents us from seeing an infinite number of them.

Figure 23.18 Olbers' paradox is similar to the view through a forest.

recognized the dilemma, astronomers leaned toward the first option. Kepler himself preferred to believe that the universe had a finite number of stars because he thought it had to be finite in space, with some kind of dark wall surrounding everything. Astronomers in the early twentieth century preferred to believe that the universe was infinite in space but that we lived inside a finite collection of stars. They thought of the Milky Way as an island floating in a vast black void. However, subsequent observations showed that galaxies fill all of space more or less uniformly. We are therefore left with the second option: The universe changes over time.

The Big Bang theory solves Olbers' paradox in a particularly simple way. It tells us that we can see only a finite number of stars because the universe began at a particular moment. While the universe may contain an infinite number of stars, we can see only those that lie within the observable universe, inside our cosmological horizon [Section 20.3]. There are other ways in which the universe could change over time and prevent us from seeing an infinite number of stars, so Olbers' paradox does not *prove* that the universe began with a Big Bang. However, there must be some explanation for why the sky is dark at night, and no explanation besides the Big Bang also explains so many other observed properties of the universe so well.

THE BIG PICTURE

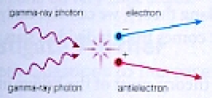
Putting Chapter 23 into Context

Our "big picture" is now about as complete as it gets. We've discussed the universe from Earth outward, and from the beginning to the end. When you think back on this chapter, keep in mind the following ideas:

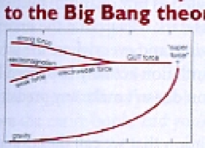
- Predicting conditions in the early universe is straightforward, as long as we know how matter and energy behave under such extreme conditions.
- Our current understanding of physics allows us to reconstruct the conditions that prevailed in the universe all the way back to the first 10^{-10} second. Our understanding is less certain back to 10^{-38} second. Beyond 10^{-43} second, we run up against the present limits of human knowledge.
- Although it may sound strange to talk about the universe during its first fraction of a second, our ideas about the Big Bang rest on a solid foundation of observational, experimental, and theoretical evidence. We cannot say with absolute certainty that the Big Bang really happened, but no other model ever proposed has so successfully explained how our universe came to be as it is.

23.1 The Big Bang

- **What were conditions like in the early universe?** The early universe was filled with radiation and elementary particles. It was so hot and dense that the energy of radiation could turn into particles of **matter** and **antimatter**, which then collided and turned back into radiation.

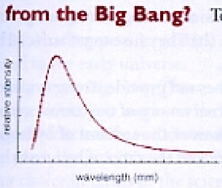


- **What is the history of the universe according to the Big Bang theory?** The universe has been through a series of eras, each marked by unique physical conditions. We know little about the **Planck era**, when the four forces may have all behaved as one. Gravity became distinct at the start of the **GUT era**, which may have ended with the rapid expansion called **inflation**. Electromagnetism and the weak force became distinct at the end of the **electroweak era**. Matter particles annihilated all the antimatter particles at the end of the **particle era**. Fusion of protons and neutrons into helium ceased at the end of the **era of nucleosynthesis**. Hydrogen nuclei captured all the free electrons, forming hydrogen atoms at the end of the **era of nuclei**. Galaxies began to form at the end of the **era of atoms**. The **era of galaxies** continues to this day.



23.2 Evidence for the Big Bang

- **How do we observe the radiation left over from the Big Bang?** Telescopes that can detect microwaves allow us to observe the **cosmic microwave background**—radiation left over from the Big Bang. Its spectrum matches the characteristics expected of the radiation released at the end of the era of nuclei, spectacularly confirming a key prediction of the Big Bang theory.

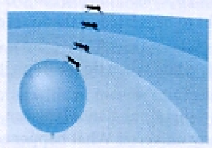


- **How do the abundances of elements support the Big Bang theory?** The Big Bang theory predicts the ratio of protons to neutrons during the era of nucleosynthesis, and from this ratio predicts that the chemical composition of the universe should be about 75% hydrogen and 25% helium (by mass). This prediction matches observations of the cosmic abundances, another spectacular confirmation of the Big Bang theory.

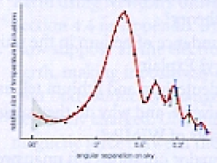
23.3 The Big Bang and Inflation

- **What aspects of the universe were originally unexplained by the Big Bang model?** (1) The origin of the density enhancements that turned into galaxies and larger structures. (2) The overall smoothness of the universe on large scales. (3) The fact that the actual density of matter is close to the critical density.

- **How does inflation explain these features of the universe?** (1) The episode of inflation stretched tiny, random quantum fluctuations to sizes large enough for them to become the density enhancements around which structures later formed. (2) The universe is smooth on large scales because, prior to inflation, everything we can observe today was close enough together for temperatures and densities to equalize. (3) Inflation caused the universe to expand so much that the observable universe appears geometrically flat, implying that its overall density of mass plus energy equals the critical density.



- **How can we test the idea of inflation?** Models of inflation make specific predictions about the temperature patterns we should observe in the cosmic microwave background. The observed patterns seen in recent observations by microwave telescopes match those predicted by inflation.



23.4 Observing the Big Bang for Yourself

- **Why is the darkness of the night sky evidence for the Big Bang?** **Olbers' paradox** tells us that if the universe were infinite, unchanging, and filled with stars, the sky everywhere would be as bright as the surface of the Sun, and it would not be dark at night. The Big Bang theory solves this paradox by telling us that the night sky is dark because the universe has a finite age, which means we can see only a finite number of stars in the sky.

EXERCISES AND PROBLEMS

For instructor-assigned homework go to MasteringASTRONOMY www.masteringastronomy.com

Review Questions

1. What is *antimatter?* How were particle-antiparticle pairs created in the early universe? How were they destroyed?
2. Explain what we mean by the *Big Bang theory.*
3. Make a list of the major eras in the history of the universe, summarizing the important events thought to have occurred during each era.
4. Why can't our current theories describe the history of the universe during the *Planck era?*
5. What are the four forces that operate in the universe today? Why do we think there were fewer forces operating in the early universe?
6. What are *grand unified theories?* According to these speculative theories, how many forces operated during the *GUT era?* How are these forces thought to be related to the four forces that operate today?
7. What do we mean by *inflation,* and when do we think it occurred?
8. Why do we think there was a slight imbalance between matter and antimatter in the early universe? What happened to all the antimatter, and when?
9. How long did the *era of nucleosynthesis* last? Explain why this era was so important in determining the chemical composition of the universe forever after.
10. When we observe the *cosmic microwave background,* at what age are we seeing the universe? How long have the photons in the background been traveling through space? Explain.
11. Briefly describe how the cosmic microwave background was discovered. How does the existence and nature of this radiation support the Big Bang theory?
12. How does the chemical abundance of helium in the universe support the Big Bang theory? Explain.
13. How do measurements of deuterium and lithium tell us about the density of the universe, and why do they suggest that most dark matter consists of WIMPs?
14. Describe each of the three major questions left unanswered by the Big Bang theory without inflation, and explain how inflation answers each of them.
15. How can observations of the cosmic microwave background—radiation released when the universe was 380,000 years old—tell us about the universe at the much earlier time when inflation occurred? Summarize the geometry, composition, and age of the universe according to observations made to date.
16. What is *Olbers' paradox,* and how is it resolved by the Big Bang theory?

Test Your Understanding

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain your reasoning. (For an example, see Chapter 1, "Does It Make Sense?")

17. Although the universe today appears to be made mostly of matter and not antimatter, the Big Bang theory suggests that the early universe had nearly equal amounts of matter and antimatter.
18. According to the Big Bang theory, the cosmic microwave background was created when energetic photons ionized the neutral hydrogen atoms that originally filled the universe.
19. While the existence of the cosmic microwave background is consistent with the Big Bang theory, we can also easily explain it by assuming that it comes from individual stars and galaxies.
20. According to the Big Bang theory, most of the helium in the universe was created by nuclear fusion in the cores of stars.
21. The idea of inflation suggests that the structure of the universe today may have originated as tiny quantum fluctuations.
22. The fact that the night sky is dark tells us that the universe cannot be infinite, unchanging, and everywhere the same.
23. We'll never know whether inflation actually happened because our model for inflation doesn't make any predictions we can test.
24. In the distant past, the radiation that we call the cosmic microwave background actually consisted primarily of infrared light.
25. The main reason that the night sky is dark is that stars are generally so far away.
26. The cosmic microwave background is our main source of information about what the universe was like at an age of about 3 minutes.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. What is the current temperature of the universe? (a) absolute zero (b) a few degrees (c) a few thousand degrees
28. What is the charge of an antiproton? (a) positive (b) negative (c) neutral
29. What happens when a proton collides with an antiproton? (a) They repel each other. (b) They fuse together. (c) They convert into two photons.
30. Which of the following does *not* provide strong evidence for the Big Bang theory? (a) observations of the cosmic microwave background (b) observations of the amount of hydrogen in the universe (c) observations of the ratio of helium to hydrogen in the universe
31. If the current density of normal matter in the universe were 10 times as great as it is now, we would expect to observe (a) more deuterium. (b) less deuterium. (c) about the same amount of deuterium.
32. Which of the following does inflation help to explain? (a) the uniformity of the cosmic microwave background (b) the amount of helium in the universe (c) the temperature of the cosmic microwave background
33. Which of the following does inflation help to explain? (a) the origin of hydrogen (b) the origin of galaxies (c) the origin of atomic nuclei
34. Which of these pieces of evidence supports the idea that inflation really happened? (a) the enormous size of the observable universe (b) the large amount of dark matter that the universe contains (c) observations of the cosmic microwave background that indicate a flat geometry for the universe

35. What is the earliest time in the universe that we can directly observe? (a) a few hundred million years after the Big Bang (b) a few hundred thousand years after the Big Bang (c) a few minutes after the Big Bang
36. Which of these options is the best explanation for why the night sky is dark? (a) The universe is not infinite in space. (b) The universe has not always looked the way it looks today. (c) The distribution of matter in the universe is not uniform on very large scales.

Investigate Further

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

37. *Life Story of a Proton.* Tell the life story of a proton from its formation shortly after the Big Bang to its presence in the nucleus of an oxygen atom you have just inhaled. Your story should be creative and imaginative, but it should also demonstrate your scientific understanding of as many stages in the proton's life as possible. You can draw on material from the entire book, and your story should be three to five pages long.
38. *Creative History of the Universe.* The story of creation as envisioned by the Big Bang theory is quite dramatic, but it is usually told in a fairly straightforward, scientific way. Write a more dramatic telling of the story, in the form of a short story, play, or poem. Be as creative as you wish, but be sure to remain accurate according to the science as it is understood today.
39. *Re-Creating the Big Bang.* Particle accelerators on Earth can push particles to extremely large speeds. When these particles collide, the amount of energy associated with the colliding particles is much greater than the mass-energy these particles have when at rest. As a result, these collisions can produce many other particles out of pure energy. Explain in your own words how the conditions that occur in these accelerators are similar to the conditions that prevailed shortly after the Big Bang. Also, point out some of the differences between what happens in particle accelerators and what happened in the early universe.
40. *Betting on the Big Bang Theory.* If you had $100, how much money would you wager on the proposition that we have a reasonable scientific understanding of what the universe was like when it was 1 minute old? Explain the reasoning behind your choice in terms of the scientific evidence presented in this chapter.
41. *"Observing" the Early Universe.* The only way we have of studying the era of nucleosynthesis is through the abundances of the nuclei that it left behind. Explain why we will never be able to observe that era through direct detection of the radiation emitted at that time.
42. *Element Production in the Big Bang.* Nucleosynthesis in the early universe was unable to produce more than trace amounts of elements heavier than helium. Using the information in Figure 17.14, which shows the mass per nuclear particle for many different elements, explain why producing elements like lithium (3 protons), boron (4 protons), and beryllium (5 protons) was so difficult.
43. *Darkness at Night.* Suppose you are Kepler, pondering the darkness of the night sky without any knowledge of the Big Bang or the expanding universe. Come up with an explanation for the darkness of the night sky that does not depend on the Big Bang theory. Propose an experiment that future scientists might be able to perform to test your hypothesis.
44. *Evidence for the Big Bang.* Alternatives to the Big Bang theory need to propose alternative explanations for many of the observations scientists have made of the universe. Make a list of at least seven observed features of the universe that are satisfactorily explained by the Big Bang theory when it is combined with the idea of inflation.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

45. *Energy from Antimatter.* The total annual U.S. power consumption is about 2×10^{20} joules. Suppose you could supply that energy by combining pure matter with pure antimatter. Estimate the total mass of matter-antimatter fuel you would need to supply the United States with energy for 1 year. How does that mass compare with the amount of matter in your car's gas tank? (A gallon of gas has a mass of about 4 kilograms.)
46. *Gravity vs. the Electromagnetic Force.* The amount of electromagnetic force between two charged objects can be computed with an inverse square law similar to that of Newton's universal law of gravitation; for the electromagnetic force, the law is:

$$F = k \times \frac{(\text{charge of object 1}) \times (\text{charge of object 2})}{d^2}$$

In this formula, the charges must be given in units of Coulombs (abbreviated C), the distance d between the objects' centers must be in meters, and the constant $k = 9 \times 10^9 \text{ kg} \times \text{m}^3/(\text{C}^2 \times \text{s}^2)$.

   a. Compute the gravitational force between your body and Earth using Newton's universal law of gravitation (see Section 4.4 or Appendix B).
   b. Now suppose all the electrons suddenly disappeared from Earth, making it positively charged, and all the protons in your body suddenly changed into neutrons, making you negatively charged. Compute the strength of the electromagnetic force between the electrons in your body and the protons in Earth. Assume that the charge per unit of mass of both you and Earth is 5×10^7 C/kg.
   c. Compare the electromagnetic force from part (b) to the gravitational force from part (a). Use that result to explain why gravity is considered weaker than the electromagnetic force.

47. *Background Radiation during Galaxy Formation.* What was the peak wavelength of the background radiation at the time that light left the most distant galaxies we can currently see? Assume those galaxies have a cosmological redshift of $z = 7.0$. What is the temperature corresponding to that peak wavelength?
48. *Expansion since the Era of Nucleosynthesis.* Compare the peak wavelength of the radiation in the universe at the end of the era of nucleosynthesis to its current peak wavelength. Assume the temperature at the end of the era of nucleosynthesis was 10^9 K. How much have the wavelengths of the photons in the universe been stretched since that time?
49. *Temperature of the Universe.* What will the temperature of the cosmic microwave background be when the average distances between galaxies are twice as large as they are today?

50. *Uniformity of the Cosmic Microwave Background.* The temperature of the cosmic microwave background differs by only a few parts in 100,000 across the sky. Compare that level of uniformity to the surface of a table in the following way. Consider a table that is 1 meter in size. How big would the largest bumps on that table be if its surface were smooth to one part in 100,000? Could you see bumps of that size on the table's surface?

51. 10^{100} *Years.* In the box "How Will the Universe End?" we found that the final stage in the history of a perpetually expanding universe will come about 10^{100} years from now. Such a large number is easy to write but difficult to understand. This problem investigates some of the incredible properties of very large numbers.
    a. The current age of the universe is around 10^{10} years. How much longer is a trillion years than this current age? How much longer is 10^{15} years? 10^{20} years?
    b. Suppose protons decay with a half-life of 10^{32} years. When will the number of remaining protons be half the current amount? When will it be a quarter of its current amount? How many half-lives will have gone by when the universe reaches an age of 10^{34} years? What fraction of the original protons will remain at this time? Based on your answers, is it reasonable to conclude that *all* protons in today's universe will be gone by the time the universe is 10^{40} years old? Explain. (*Hint:* See Mathematical Insight 8.1.)
    c. Suppose you were trying to write 10^{100} zeros on a piece of paper and could write microscopically, so that each zero (including the thickness of the pencil mark) occupied a volume of 1 cubic micrometer—about the size of a bacterium. Could 10^{100} zeros of this size fit in the observable universe? Explain. (*Hint:* Calculate the volume of the observable universe in cubic micrometers by assuming it is a sphere with a radius of 14 billion light-years. The volume of a sphere is $\frac{4}{3}\pi r^3$; 1 light-year $\approx 10^{15}$ meters; 1 cubic meter $= 10^{18}$ cubic micrometers.)

52. *Daytime at "Night."* According to Olbers' paradox, the entire sky would be as bright as the surface of a typical star if the universe were infinite in space, unchanging in time, and the same everywhere. However, conditions would not need to be quite that extreme for the "nighttime" sky to be as bright as the daytime sky.
    a. Using the inverse square law for light from Mathematical Insight 15.1, determine the apparent brightness of the Sun in our sky.
    b. Using the inverse square law for light, determine the apparent brightness our Sun would have if it were at a distance of 10 billion light-years.
    c. From your answers to parts (a) and (b), estimate how many stars like the Sun would need to exist at a distance of 10 billion light-years for their total apparent brightness to equal that of our Sun.
    d. Compare your answer to part (c) with the estimate of the total number of stars in our observable universe from Mathematical Insight 1.3. Use your answer to explain why the night sky is much darker than the daytime sky. How much larger would the total number of stars need to be for "night" to be as bright as day?

Discussion Questions

53. *The Moment of Creation.* You've probably noticed that, in discussing the Big Bang theory, we never quite talk about the first instant. Even our most speculative theories at present take us back only to within 10^{-43} second of creation. Do you think it will *ever* be possible for science to consider the moment of creation itself? Will we ever be able to answer questions such as *why* the Big Bang happened? Defend your opinions.

54. *The Big Bang.* How convincing do you find the evidence for the Big Bang model of the universe's origin? What are the strengths of the theory? What does it fail to explain? Overall, do *you* think the Big Bang really happened? Defend your opinion.