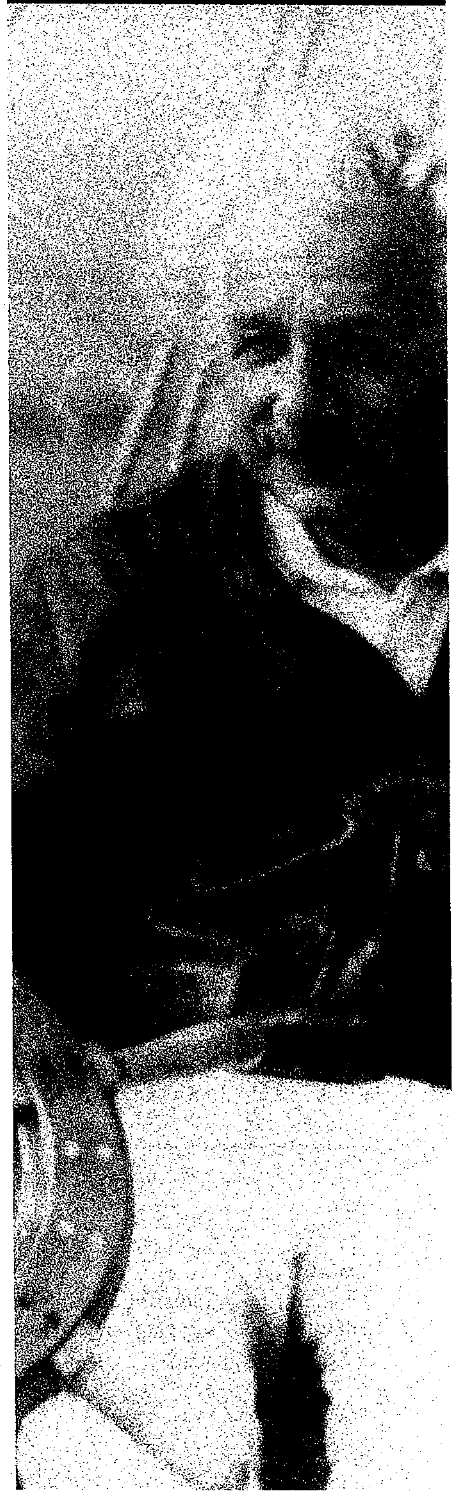
CHAPTER 11

# Einstein's Universe and the New Cosmology

**Einstein's Pegasus**
There's Einstein riding on a ray of light,
In which he cannot see his face in flight
Because his jesting image, I now understand,
Won't ever reach the mirror since its speed,
Too, is the speed of light. He rides, this fleeting day,
As if on Pegasus, immortal steed
Of bridled meditation, past the Milky Way,
Out to my mind's Andromeda, where I,
Also transported, staring at a windless pool,
Watch his repaired reflection whizzing by.
Though he can't see himself, this self-effacing fool
Who holds all motion steady in his head,
I won't forget his facing what he cannot see
In thought that binds the living and the dead,
And ride with him, outfacing fixed eternity.

**Robert Pack, Middlebury College, 1991**



The special theory of relativity describes the observations of nonaccelerated observers. What about accelerated observers? Einstein found a surprising connection between acceleration and gravity, and between gravity and a feature best described as "warps in spacetime." Section 11.1 presents these key ideas.

I've devoted the remainder of the chapter to cosmology: the study of the origin, structure, and evolution of the large-scale universe. The general theory of relativity is science's basic tool for such matters. You are living in the golden age of cosmology. It started in 1992 when microwave receivers on orbiting satellites gathered the first detailed image of the "cosmic microwave background" showing the earliest light from the creation of the universe. It continues today with the search for dark matter, dark energy, and an elusive microscopic particle known as the "Higgs boson." Cosmology is inspired by some of the oldest questions ever asked, and is perhaps the oldest story ever told. For thousands and probably millions of years, humans have looked for answers to questions such as: How did all this come to be? Where did Earth come from? What is the layout of the universe? Where do humans fit in? There's been plenty of speculation about all this, but now for the first time we are finding evidence-based answers, answers that have at least as much to do with physics as with astronomy. I hope you'll share in the excitement by pondering the discoveries and concepts in this chapter.

Section 11.2 presents the "big bang" that created our universe and evidence that it actually occurred. Einstein's connection between gravity and warped spacetime leads to a new way of viewing, in Section 11.3, the overall structure and expansion of the universe. Section 11.4 presents the recent microwave image of the big bang shortly after it occurred and its implications for the overall shape of the universe. Section 11.5 presents a surprising and exciting development: The universe is filled with enormous amounts of "dark matter" that doesn't interact with light and so has not yet been directly observed. Section 11.6 describes two additional completely unexpected developments: the accelerating universe and the mysterious "dark energy" pushing this acceleration. Section 11.7 presents a recent hypothesis on how, and perhaps even why, the big bang banged. Because these results aren't easy to believe, I've included quite a few "How Do We Know" subsections.

## 11.1 EINSTEIN'S GRAVITY: THE GENERAL THEORY OF RELATIVITY

The special theory of relativity begins with the principle that the laws of physics are the same for all unaccelerated observers. What about accelerated observers? This is the starting point for the general theory of relativity.

You've probably noticed, when riding in an elevator accelerating upward from a building's ground floor, that you felt squashed down, heavy, as though there were more gravitational pull on you than usual. This connection between acceleration and "apparent gravity" runs deeper than you might think. For example, imagine being inside an accelerating rocket ship in outer space, far from all planets and stars so that there are no gravitational forces [**Figure 11.1(a)**]. If the rocket's acceleration is 9.8 m/s$^2$ or 1$g$ ("one gee"), you will feel the same as you do when you are stationary on Earth [Figure 11.1(b)]. The reason is that, according to Newton's law of motion, the rocket's floor must push upward on the bottoms of your shoes in order to accelerate you at 1$g$. Because this push is quantitatively equal to your weight on Earth, you feel the same force against your feet as you do at rest on Earth. So accelerations mimic the effects of gravity.

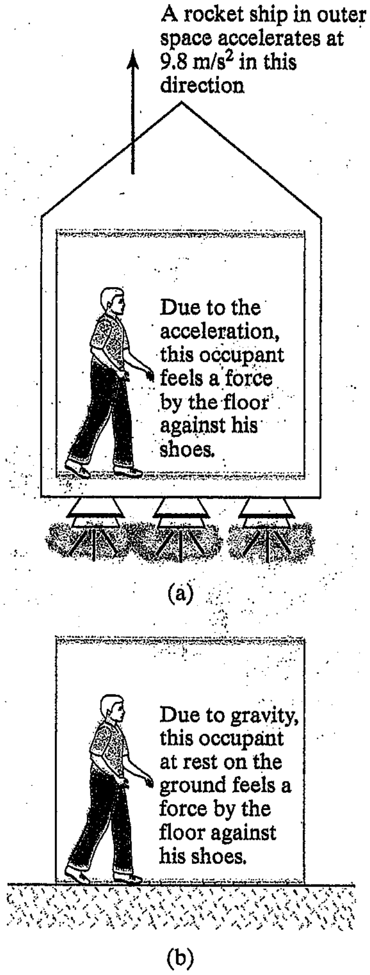


**Figure 11.1**
Acceleration is indistinguishable from gravity. The occupant cannot tell the difference.

If you were in a rocket accelerating smoothly at 1$g$ through outer space, could you tell, without communicating with the world outside the rocket, that you were actually in space and not at rest on Earth's surface? Think about it. You might try dropping a stone to see how it falls (**Figure 11.2**). But your rocket is accelerating at 1$g$ so the floor accelerates upward to meet the stone. From your point of view inside the rocket, the stone "falls" down to the floor with an acceleration of 1$g$. Furthermore, Galileo's law of falling (Chapter 3) is valid: A large-mass stone and a small-mass stone, released together, reach the floor (or rather, the floor reaches them) at the same time. You also could throw a stone horizontally (**Figure 11.3**). Because of the rocket's upward acceleration, the stone gets closer to the floor as it moves across the rocket. As you view it, the stone "falls" to the floor exactly as though it were thrown horizontally on Earth.

It seems it's not easy to perform an experiment inside your rocket ship that can tell you whether you're at rest on Earth's surface or moving through space with a 1$g$ acceleration.

Einstein made this reasoning into a fundamental principle that's similar to the principle of relativity. The principle of relativity says that there is no way, from within your own laboratory, to distinguish a state of rest from motion at constant

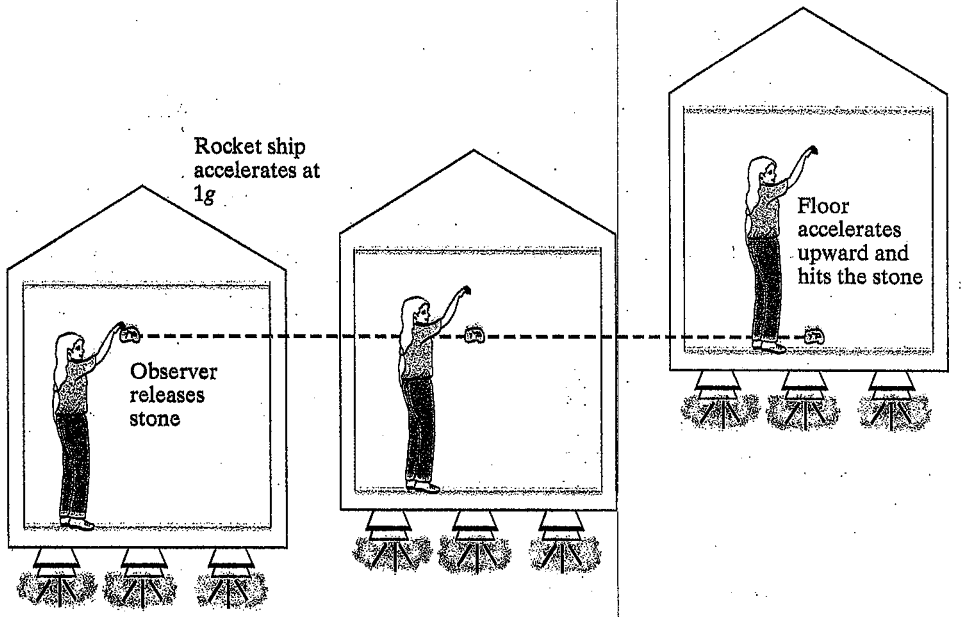


**Figure 11.2**
If you release a stone inside an accelerating rocket in outer space, it will appear to you that the stone falls "down" to the floor, just as though you were on Earth and feeling the effects of gravity.

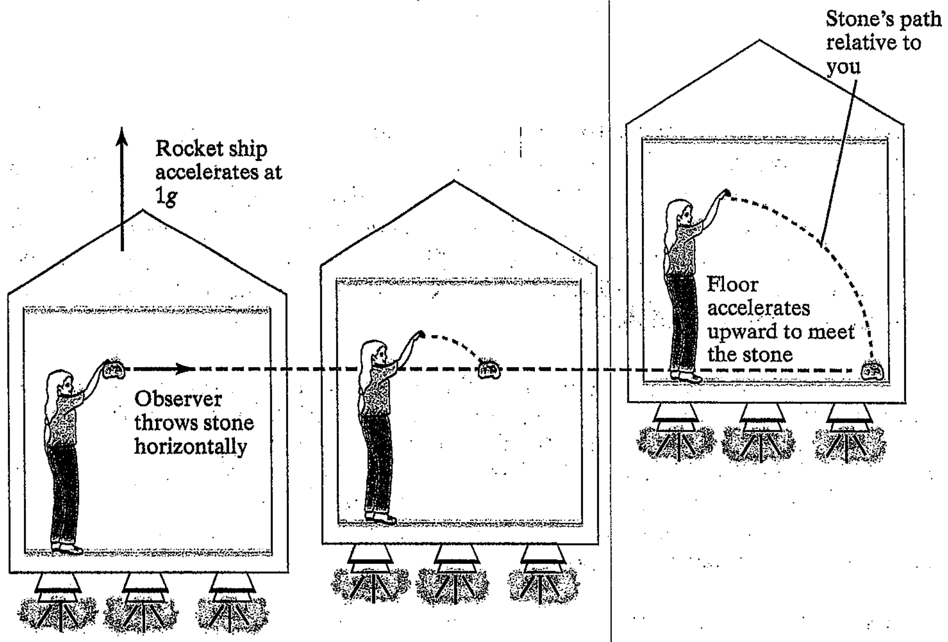


**Figure 11.3**
If you throw a stone inside an accelerating rocket in outer space, it will appear to you that the stone falls to the floor as though you were on Earth and feeling the effects of gravity.

velocity. The new principle states that there is no way, from within your own laboratory, to distinguish the effects of gravity from the effects of acceleration. Because it says that gravity is equivalent to acceleration, we call this

**The Equivalence Principle**

No experiment performed inside a closed room can tell you whether you are at rest in the presence of gravity or accelerating in the absence of gravity.

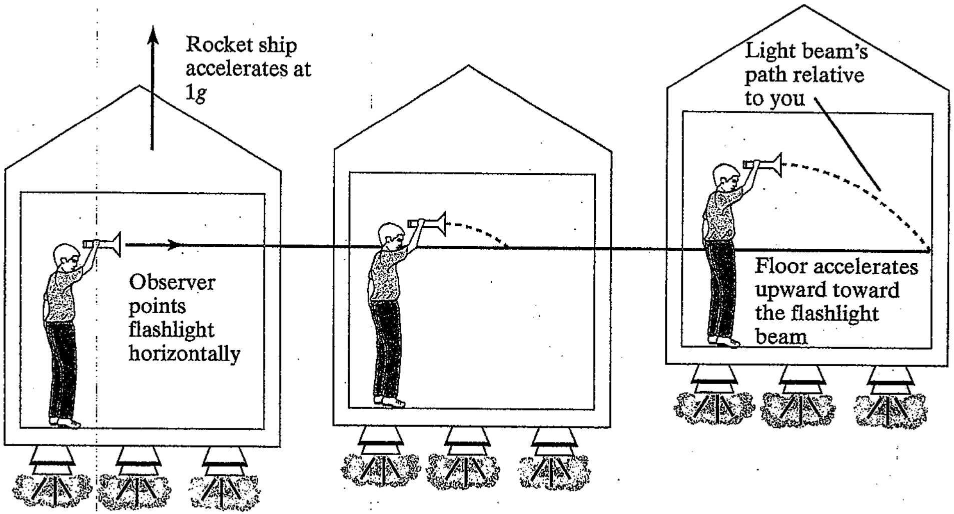


**Figure 11.4**
If you turn on a flashlight inside an accelerating rocket in outer space, the light beam bends relative to you.

Light beams play a central role in the general theory just as they do in the special theory. How do accelerations affect light beams? If you accelerate through outer space and you turn on a flashlight horizontally, the light beam must bend downward relative to you (**Figure 11.4**), just like the path of a horizontally thrown stone (Figure 11.3). The equivalence principle implies that this experiment must come out the same way if performed in a stationary room in the presence of gravity. So **gravity must bend light.**

**How do we know that gravity bends light?** Earth's gravity is too weak to bend light very much. But the sun is massive enough to measurably bend the light from distant stars as the light passes close to the sun. The first measurement of this effect was made during a total eclipse of the sun in 1919, when astronomers could photograph the stars that appear near the edge of the sun (**Figure 11.5**). Measurements of these stars' positions showed that the starlight does bend as it passes the sun and that the amount of curvature agrees with Einstein's predictions.

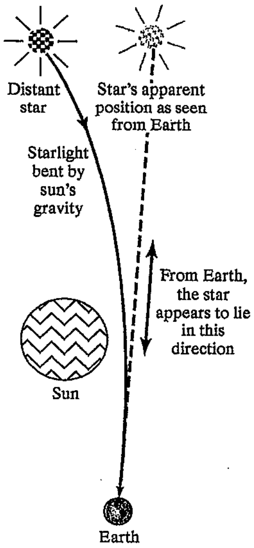


**Figure 11.5**
Because the sun bends light beams, we can (during a total eclipse) see stars that are behind the sun.

Recall that the constancy of lightspeed led Einstein to the surprising discovery that time is relative. Similarly, the gravitational bending of light implies a surprising property of space, related to the concept of *straightness*. Just as time is a physical property of the universe that can be measured by a light clock, straightness is a physical property that can be defined as the path followed by a light beam. In fact, surveyors often use laser beams to determine straightness, and you use light beams to determine straightness when you aim a gun by sighting along its barrel. But what can it mean to say that gravity bends light beams, when light beams themselves are the definition of straightness? Just as the slowed ticking of moving light clocks implies that time itself slows down, Einstein saw that the bending of light beams means that *space itself is bent, or curved, or warped, by gravity*. The path of a light beam is best described as the "straightest possible" path. In a curved space, even the straightest possible path must be curved.

Space is warped. It's an odd concept. It took an Einstein to think of it, but it's not something that Einstein, or you or anybody else, can visualize. As Stephen Hawking (**Figure 11.6**) remarked, "It is hard enough to visualize ordinary three-dimensional space, let alone warped three-dimensional space." The difficulty is that space has only three dimensions (length, width, and height), so there is no higher dimensionality from which to view the curvature of our three-dimensional space the way you can view, from your three-dimensional perspective, the bending of a two-dimensional sheet of paper.

The best anybody can do is visualize analogies to this important idea of curved space. For example, a flat tabletop is two-dimensional (the *surface* has length and width only) and can be considered to be a "flat two-dimensional space" (**Figure 11.7**). If we put a warp in it, a depression perhaps (**Figure 11.8**), the surface becomes a *warped* two-dimensional space. For another example, the *surface* (not the inside) of a sphere is a curved two-dimensional space. The two standard dimensions on the surface of a globe, for example, are called longitude (angular distance east or west of a circle running through the two poles and through Greenwich, England) and latitude (angular distance north or south of the equator). In this curved two-dimensional space, the straightest possible lines (analogous to the paths of light beams in curved three-dimensional space) are the "great circles," such as the equator and the circles of longitude running through the poles.

Suppose you were a two-dimensional creature inhabiting a two-dimensional spherical space, something like a flat ant crawling on the surface of a large globe. How could you tell that your space was curved? You couldn't stand outside or inside the globe's surface, in the third dimension, to see that you are on a spherical surface, because there is no such third dimension in this two-dimensional analogy. One way you could learn that your space is curved is by performing geometry experiments. For instance, two lines, beginning parallel and extending as straight lines (or straightest lines, as perceived from our three-dimensional vantage point), should eventually meet (**Figure 11.9**). Similarly, you cannot directly see the curvature of three-dimensional space, but you can perform experiments to determine whether our space is curved. The 1919 experiment that measured the curvature of light near the sun was just such a geometry experiment. It found that even the straightest path, the path of a light beam, bends near the sun. We conclude that three-dimensional space itself is curved.

**Figure 11.6**
Stephen Hawking has made remarkable contributions to astrophysics and cosmology.

Then I would have felt sorry for the dear Lord, for the theory is correct.

Einstein's reply when asked how he would have felt if the 1919 Solar Eclipse observations had disagreed with his General Theory of Relativity.

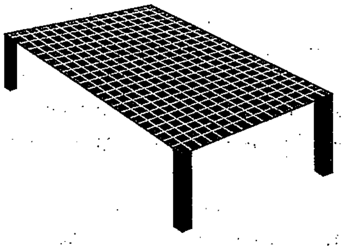


**Figure 11.7**
A flat tabletop is a flat two-dimensional space.

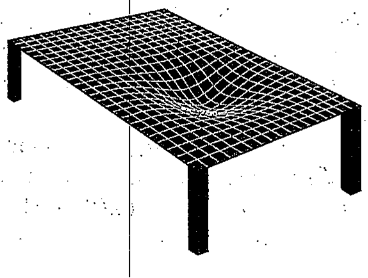


**Figure 11.8**
If you warp a flat two-dimensional space, it becomes a curved two-dimensional space.

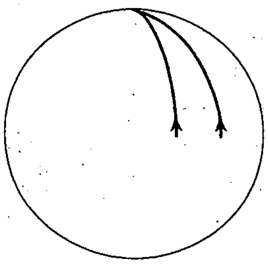


**Figure 11.9**
In a two-dimensional spherical space, two lines that start out parallel and extend as "straight" (or straightest) lines will eventually meet.

At this point, many students develop the misconception that there must be a fourth spatial dimension into which three-dimensional space is curving. This is wrong. Our two-dimensional analogy is meant to be imagined with no reference to any "embedding" of those two dimensions in a third dimension; the real three-dimensional space is curved despite the absence of a fourth spatial dimension into which three-dimensional space is curving.

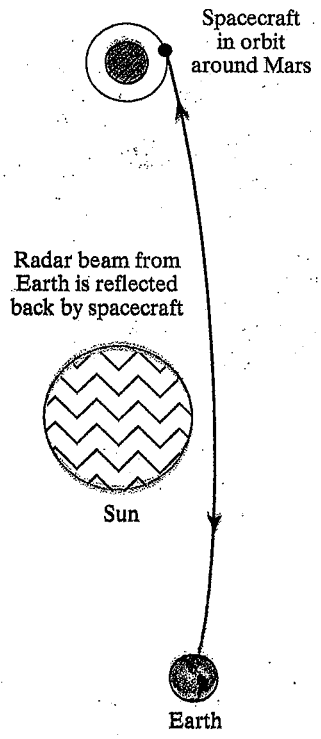


**Figure 11.10**
An experiment to measure the total travel time for a radar beam to get to Mars and back.

**How do we know that space is curved?** But does the bending of light really show space to be curved or does it merely show that light beams bend in ordinary or "flat" three-dimensional space? The latter possibility was ruled out by an experiment in 1972 in which a spacecraft orbiting Mars beamed back radar signals sent from Earth (**Figure 11.10**). The radar beam's travel time was measured at a time of year when the line of sight from Earth to Mars passed near the sun. This travel-time measurement can tell whether the bent light beam travels through a flat space or through a warped space. Here's how.

It's easy to use the observed curved path to predict the travel time in a flat space by making a scaled-down drawing of the curved path on a flat sheet of paper and seeing how much longer it is than a straight line. In the experiment, the answer was about 10 m, so if the radar beam was merely bending in a flat space, it should have been delayed by about 30 billionths of a second, the time taken by light (and radar) to travel 10 m. But you can't use a flat sheet of paper to measure distances in a warped space, for the same reason that you can't determine the distance from Los Angeles to London by making measurements on a flat map: The "scale" keeps changing because of the curvature. Einstein's formulas predict a delay of 200 millionths of a second, 7000 times longer than the predicted delay in a flat space. The experiment confirmed Einstein's prediction.

I have so far ignored one fact that I now must mention. Recall from Chapter 10 that space and time are tangled up with each other. For example, to measure the width of a moving window, you need at least two clocks to ensure that you measure the two sides of the window at precisely the same instant. So distance measurements involve time measurements. In general relativity, this tangling of space and time means that any warping of space must also distort *time*, causing clocks (in other words, time) to go slower in stronger gravitational fields. It's really space and time together, or **spacetime**, that is distorted by masses. Spacetime is not an especially subtle or difficult idea. It's not hard to imagine two or three of its dimensions, but impossible to imagine all four at once. For example, if you've ever graphed the position "x" of an object moving along a straight line versus the object's time of travel "t," you've graphed the motion of an object in spacetime.

The general theory of relativity revolutionized our view of gravity and of space and time. Newtonian physics viewed space and time as a passive, unchanging background against which events unfolded, while modern physics views spacetime as an active and changing physical participant in events. Spacetime forms a kind of fabric that can be molded by masses (**Figure 11.11**), much as a hammer can bend a sheet of metal. Spacetime has a *shape*, a shape that is molded by matter and that affects the motion of matter and radiation through space.

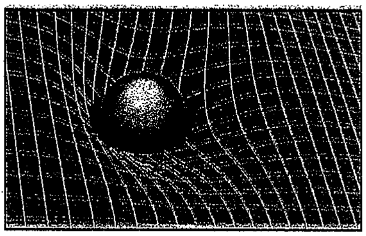


**Figure 11.11**
Masses such as the sun cause space to curve.

For familiar situations on Earth such as the fall of a stone, general relativity's predictions are nearly identical to Newton's.[1] For exotic situations such as near a

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[1] Even on Earth, the small differences from Newtonian predictions are important for practical applications requiring extreme accuracy. For example, the global positioning system (GPS) depends on satellites to provide an accurate determination of the position of any GPS receiver on Earth. It's crucial that all 24 GPS satellites use the same time to a high degree of accuracy. For this, scientists must take the effects of both special and general relativity into account.

black hole or during the creation of the universe, general relativity's predictions differ enormously from Newton's. Conceptually, the two theories differ radically. In Einstein's theory, gravitational effects such as Earth's circular motion around the sun are not caused by forces at all but are instead due entirely to the curvature of spacetime. Earth's orbit is pulled into a circle not by the force of gravity, but rather because the sun warps spacetime and Earth simply "falls" freely (experiencing no force at all) along those warps. Earth *must* move along a curved path in spacetime, because spacetime is curved. To ward off a common misconception, I'm not saying here that *space* is curved into a circle around the sun and that Earth follows these circles. Instead, *spacetime* is curved in such a way that Earth moves in a circle in the spatial dimensions while moving toward increasing time in the time dimension, producing a spiral in spacetime.

**How do we know that general relativity is accurate?** What with curved space, bending lightbeams, and spacetime, this theory introduces some unusual concepts. It would be natural for you to question its validity. So it's reassuring to know that scientists have checked the theory frequently and carefully and it has not yet failed a single test. The most demanding test was reported in 2006, and involved a pair of pulsating neutron stars (Section 5.4) that orbit each other in our own galaxy at 2000 light-years from Earth. Imagine two stars, each more massive than the sun yet squeezed down by gravity to a diameter of only a few kilometers, each containing a billion tonnes of material in every cubic centimeter, one star spinning an incredible 44 times per second and the other at 3 seconds per revolution, each sending out with each revolution a radio beep similar to a rotating lighthouse beacon, and separated from each other by only about 3 times the distance from Earth to the moon—close enough that each star affects the pulses of the other. The stars are converging at 7 mm per day, and will merge in a galaxy-shaking collision in 85 million years. The enormous gravitational fields created near these tiny but massive stars, the regularity of the stars' motions and their clocklike radio signals make this system a perfect "laboratory" for testing many quantitative details of general relativity in a situation where spacetime is predicted to be strongly bent by gravity, and where Newtonian gravity is far wrong. According to Ingrid Stairs, a member of the team who reported the first measurements, "general relativity does a perfect job of describing what we know of the system so far." The results showed that, despite the extreme gravity, the theory of general relativity is accurate to within the team's measurement uncertainty of 0.05%.

A similar but even more mind-blowing observation was reported in 2008 when scientists discovered the largest known black hole (Section 5.4) at the center of a galaxy 3.5 billion light-years from Earth. This black hole has the mass of 18 billion suns. To make matters even more interesting, they found a smaller 100-million-sun black hole orbiting the larger black hole every 12 years. Again, this system is a perfect laboratory to observe general relativistic effects. These observations have been done, and they fully agree with general relativity while ruling out several competing theories that had been proposed as alternative theories of gravity. Like the neutron stars, the two black holes are converging and will merge in about 10,000 years, a collision that will literally shake spacetime in a manner that should be detectable here on Earth, across 25% of the observable universe.

**▶ CONCEPT CHECK 1** Since accelerations can mimic the effects of gravity, accelerations should be able to cancel gravity. Thus, a person could experience weightlessness by (a) blasting off from Earth, straight upward, at an acceleration of 1g; (b) falling from a high place such as a diving board or airplane (skydiving); (c) orbiting Earth; (d) standing on the surface of the moon.

CONCEPT CHECK 2 The equator is a "straightest possible" line on the surface of a globe. Are the other east-west circles of latitude "straightest possible" lines? (a) Yes. (b) No, they curve more than the equator's curvature. (c) No, they curve less than the equator's curvature. (d) No, despite the fact that their curvature is the same as the equator's curvature.

## 11.2 THE BIG BANG

> You don't have to search far to locate where the big bang occurred, for it took place where you are now as well as everywhere else; in the beginning, all locations we now see as separate were the same location.
>
> String Theorist (See Chapter 17) Brian Greene in *The Elegant Universe*

You are living in the golden age of **cosmology:** the study of the origin, structure, and evolution of the large-scale universe. I will take full advantage of that fact by presenting some of the mind-blowing recent cosmological discoveries. The golden age began in 1992 when an observing satellite charted the first detailed map of the early universe. The keys to the new cosmological discoveries are the wonderful new observing instruments such as the Hubble Space Telescope. The key to understanding these discoveries is the general theory of relativity.

When applied to the universe as a whole, general relativity predicts the possible ways our three-dimensional universe could evolve throughout past and future time. When supplemented with certain astronomical observations (described in the following discussion), general relativity leads to a striking description of the origin and evolution of the universe: About 14 billion years ago,[2] the universe began in a single event called the **big bang** that created the different forms of energy and matter, causing the "observable" universe (the portion that can be observed with telescopes) to expand from a much smaller initial size. The reality of the big bang is strongly confirmed by serval independent lines of observational evidence, but the theoretical understanding of how and why this event occurred is just beginning (Section 11.7).

**Figure 11.12**
The Wilkinson Microwave Anisotropy Probe (WMAP) leaving the Earth/moon system, headed for a gravitational blance point in space known as "L2." In 2003, this satellite looked nearly 14 billion years back in time to observe our universe when it was in its infancy—about 400,000 years old. This is comparable to viewing a baby picture of an 80-year-old man taken when he was less than one day old. WMAP used the moon to gain velocity for a slingshot to L2.

**How do we know there was a big bang?** Four independent lines of evidence support the big bang theory:

1. Astronomers first hypothesized the big bang in 1929 because they discovered evidence that all the galaxies throughout the universe are receding from one another just as if they had been driven apart by an explosion. Extrapolating backwards in time from the speeds and distances we see today, the galaxies should have all been together 14 billion years ago.
2. In 1964, radio astronomers first detected the **cosmic microwave background**, the faint afterglow that still fills the universe from the hot initial explosion. The radiation has now cooled all the way down to −270°C.[3] This cold radiation has too little energy to be visible and is observable today only as faint radio static in the microwave and radio regions of the spectrum. Its observed characteristics, such as its temperature, agree with the big bang theory's predictions.
3. In 1992 and again in 2003, observing satellites mapped the cosmic microwave background arriving at Earth from all directions in space (**Figure 11.12**). The results (**Figure 11.13**) showed that this radiation contains subtle and highly complex "ripples" of precisely the sort expected if the initial big bang did indeed develop into the structured universe of galaxies and clusters of galaxies that we see today. The existence of the radiation mapped in Figure 11.13, and the close relationship between that radiation and the universe we see around us today, are strong evidence for the big bang theory.

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[2] More precisely, 13.73 billion years with a surprisingly small 1% margin of error.

[3] This is just 3 degrees above absolute zero, the lowest possible temperature, the temperature at which all microscopic motion is the least it can be without violating the quantum uncertainty principle (Chapter 13).

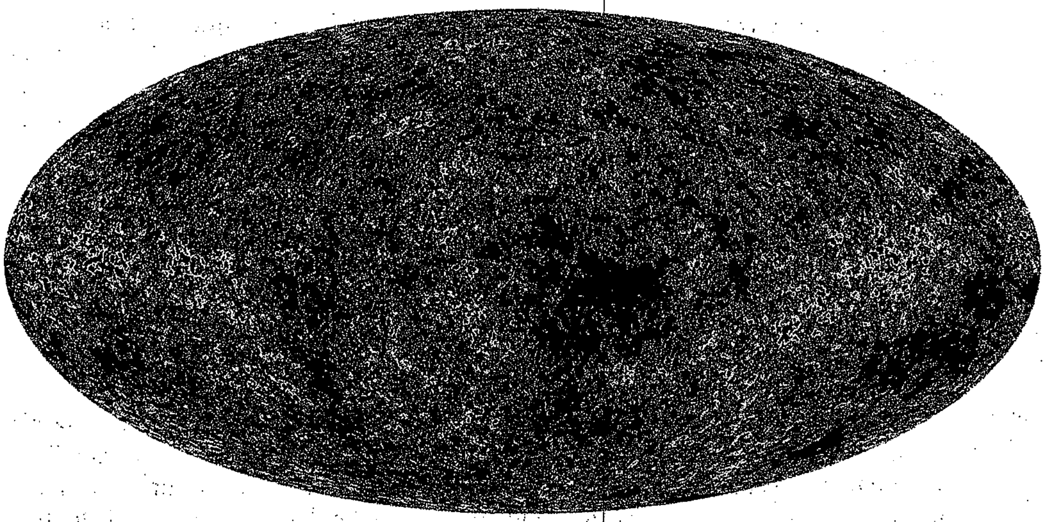


**Figure 11.13**

First light: A "fossil" of the creation of the universe. This map, a portrait of the 14-billion-year-old microwave whisper that now remains from the mighty flash of radiation that was released a mere 380,000 years after the big bang, shows the temperature differences in the universe as it existed at the time the radiation was released; darker regions are slightly cooler, lighter regions are warmer. The map shows every direction in space; think of horizontal and vertical axes going through the map's center, with units in angular degrees extending 360° along the horizontal axis and 180° along the vertical axis. Although the expansion of the universe has by now stretched the fabric of space so much that the radiation has stretched into the microwave region of the spectrum, you are looking at a photograph ("microwave-graph" actually) of the first light that traveled through the universe. Before this time, the universe was so hot that its atoms were electrically charged, which prevented light from traveling through space. Thus, the cosmic microwave background acts like a light-emitting curtain, beyond which we cannot see. It is the oldest, largest, and furthest observable structure known to science.

4. The fourth line of evidence concerns the creation of the universe's first chemical elements. The earliest kinds of ordinary matter, formed during the first thousandth of a second of the big bang, were protons, neutrons, and electrons. Conditions during just the next 3 minutes were right for protons and neutrons to "fuse" together into more complex nuclei. After these 3 minutes, the universe was too cool and too dilute for protons and neutrons to continue fusing (Chapter 15). Well-developed and highly reliable nuclear physics calculations predict that at the end of these 3 minutes, 75% of the original protons still remained, while 25% of the original protons had fused with neutrons to form four other types of nuclei, labeled ${}^2_1$H, ${}^3_2$He, ${}^4_2$He, and ${}^7_3$Li. The remaining single protons are ordinary hydrogen nuclei, labeled ${}^1_1$H. The universe was then made of two different types of hydrogen, two types of helium, and one type of lithium, in the proportions stated in Table 11.1.

   Astronomers have made measurements of the light or "spectra" (Chapter 13) from the oldest stars, stars that presumably formed from the original material created in the big bang and that have changed little since that time. These measurements show relative amounts of the five isotopes that are in excellent agreement with the theoretically predicted amounts of **Table 11.1**. This detailed quantitative agreement between observations and the big bang theory's predictions for five different nuclear types is strong evidence for the theory. The prediction and confirmation of ${}^2_1$H is especially compelling, because nuclear physics predicts that there is essentially no process anywhere in the universe, other than the big bang, that could have made this material.

The big bang is as real as the "snow," or interference, that you can see on an old analog (pre-digital) TV screen when the power is on with no station tuned in. Cosmic microwave background radiation causes some of this interference. The echo of the big bang is all around you!

**Table 11.1**

Predicted nuclear composition of universe at about 3 minutes after start of big bang. Current observations of the oldest material in the universe agree well with these predictions.

| Nuclear type | Relative concentration by mass |
|---|---|
| ${}^1_1$H | 75% |
| ${}^2_1$H | 5–10 parts in 100,000 |
| ${}^3_2$He | 2–5 parts in 100,000 |
| ${}^4_2$He | 25% |
| ${}^7_3$Li | 2–5 parts in 10 billion |

In the patterns of the subtle temperature differences in the cosmic microwave background in different directions we are learning to read the Genesis story of the expanding universe. The resulting origin story will be the first ever based on scientific evidence and created by a collaboration of people from different religions and races all around the world, all of whose contributions are subjected to the same standards of verifiability.

Nancy Ellen Abrams, Lawyer and Writer, and Joel Primack, Astrophysical Theorist, Writing in the Journal *Science*

The universe is still made mostly of hydrogen and helium, although heavier elements created since the big bang now contribute a small percentage. Nearly all the hydrogen and helium can be traced back to the big bang. Although our bodies contain no helium, the hydrogen forged 14 billion years ago in the big bang is one of the most prevalent elements in your body and in all living organisms.

**CONCEPT CHECK 3** The gold nuclei in the universe were (a) all created in the big bang; (b) all created sometime after the big bang; (c) created partly during the big bang, and partly after.

## 11.3 THE POSSIBLE GEOMETRIES OF THE UNIVERSE

The expansion of the universe may be the most important fact ever discovered about our origins. The key to understanding it is to not take the term "big bang" too seriously. It was not like the explosion of a bomb that happened *in* time and space. Rather, the big bang *created* time and space. Time and space are part of the universe, not the other way around. As the universe expands, it makes its own time and space. The universe is expanding, but it is not expanding into anything because there is no space "outside" of the universe. So space started small and has been geting bigger ever since.

One of the predictions of general relativity is that three-dimensional space can't remain static but must always either expand or contract. It's remarkable that even space itself must continually change. Everything, it seems, is active and changing: The stars are born and die, life on Earth evolves, you and I are born and will die, and even space itself must always expand or contract.

Direct evidence for the **expansion of the universe** comes from astronomical observations of other galaxies outside our Milky Way galaxy. Distant galaxies are moving away from us, and the more distant galaxies move away faster. But the galaxies are not just moving away from our particular galaxy; they are all moving away from one another. Regardless of which galaxy you live in, you will observe the other galaxies moving away from you. It's like a loaf of raisin bread expanding as it bakes: If you were standing on any one of the raisins observing the other raisins, you would observe all of them moving away from you, and more distant raisins would move away from you faster.

To visualize the expansion of our entire curved three-dimensional universe, we must imagine a two-dimensional analogy as in Section 11.1. Imagine that the surface of a partially inflated balloon is a two-dimensional universe, similar to the ant and globe analogy of Section 11.1. To represent the galaxies, imagine two-dimensional (flat) raisins glued to the surface. Remember that, in this two-dimensional analogy, you must imagine that the inside and outside of the balloon don't exist; only the two-dimensional *surface* of the balloon is supposed to exist.

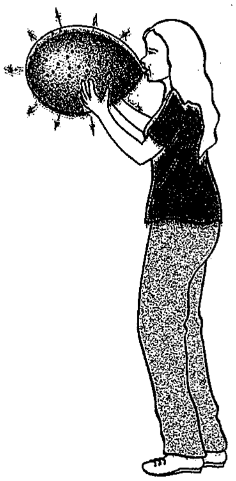
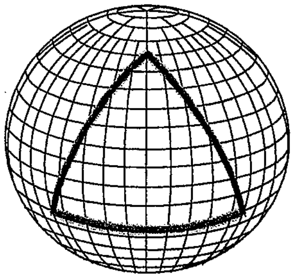


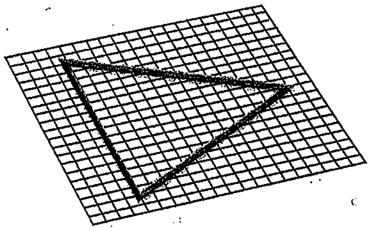
**Figure 11.14**
The two-dimensional surface of an expanding balloon is a two-dimensional representation of the expansion of the three-dimensional universe. As space, represented by the balloon's surface, expands, the galaxies, represented by flat raisins glued to the balloon, move farther apart. Although this two-dimensional analogy has the universe expanding into the empty space outside the balloon, there is no space outside the real three-dimensional universe.

Now imagine that the balloon inflates (**Figure 11.14**), representing the expansion of the universe. Note that, as the balloon expands, the distance between all the raisins increases. No matter which raisin you are standing on, all the other raisins move away from you. No raisin is at the center of this balloon universe, in fact the *surface* of the balloon has no center. In agreement with the philosophy of the Copernican revolution (Chapter 1), this universe is, on average, the same all over. Note that the galaxies are at rest relative to the balloon's surface. It's not really the raisins that are moving; instead, the space between the raisins is expanding. In the real three-dimensional universe, gravity holds each galaxy (also each star and each planet) together in a relatively fixed size and shape, while the space between the galaxies expands. Note also that no galaxy is at the edge of the balloon universe, because the balloon universe has no edge. And neither does the real three-dimensional universe.

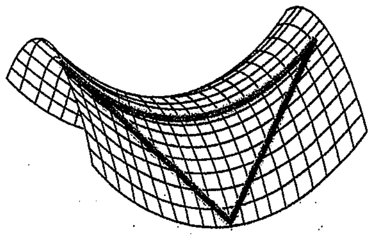
According to general relativity, the possible shapes or **geometries** for the large-scale structure of the three-dimensional universe fall into three categories. **Figure 11.15** shows the two-dimensional analogs of these three-dimensional geometries. A **closed universe** bends back on itself to form a sphere. If you lived in a closed universe, you could detect this from the fact that straight (that is, straightest) lines that start out parallel eventually meet (Figure 11.9), and the angles of a triangle add up to more than the normal 180°, as you can see from Figure 11.15. Although a closed universe has only a finite extent, the other two geometries have infinite total extents and so only a portion of these surfaces can be shown in the figure. A **flat universe** has no overall large-scale curvature (in all three geometries there will be smaller-scale warps caused by stars, black holes, galaxies, and other objects) and has the normal Euclidean geometry with which you are familiar—parallel lines remain parallel, and the angles of a triangle add up to 180°. An **open universe** is analogous to a saddle-shaped surface; in such a universe, straight lines that start out parallel eventually diverge from each other, and the angles of a triangle add up to less than 180°.



(a) Closed geometry



(b) Flat geometry



(c) Open geometry

**Figure 11.15**
Two-dimensional analogs of the possible large-scale geometries of the three-dimensional universe, as predicted by general relativity. A closed universe bends back on itself to form a three-dimensional spherical space; in such a universe, the angles of a triangle add up to more than the normal 180° and the total volume is finite. A flat universe has no overall large-scale curvature; it has the normal Euclidean geometry where the angles of a triangle add up to 180°, and an infinite total volume. An open universe is analogous to a saddle-shaped surface; in such a universe, the angles of a triangle add up to less than 180° and the total volume is infinite.

Regardless of which of the three geometries our actual universe might have, if you follow a straight (straightest) path, you will never come to an edge or to the center of the universe. In the open and flat universes, this is because the universe is infinite in extent. In the closed universe, it is because straight (straightest) lines simply curve back to where they started. In such a universe, if you head in an absolutely straight line for many billions of light-years, you will reach your starting point.

**CONCEPT CHECK 4** The universe is expanding. Is everything in the universe expanding? (a) Yes. (b) No, the distances between the galaxies are not expanding. (c) No, the Milky Way galaxy is not expanding. (d) No, our solar system is not expanding. (e) No, Earth is not expanding.

## 11.4 THE SHAPE OF THE UNIVERSE

The revolution in cosmology has been driven by a revolution in observational techniques. Until 1992, observations having cosmological significance were few and far between and highly imprecise. Cosmology was of necessity highly theoretical and conjectural. The age of precision cosmology began in 1992 with the first observation of the details of the cosmic microwave background, similar to the far more detailed Figure 11.13.

Figure 11.13 is a "microwave photograph," similar to an infrared photograph (Chapter 9), showing the temperature variations in the background radiation emitted by the big bang. The light regions are slightly warmer than the dark regions. This radiation was emitted just 400,000 years after the big bang. Before that time, the temperature of the universe was so high that protons and electrons moved too rapidly to stick together to form hydrogen atoms. The resulting mix of electrically charged protons and electrons immediately absorbed any radiation present. At 400,000 years, the universe had cooled enough for electrons to combine with protons to form neutral hydrogen atoms, and radiation propagated through space for the first time. The microwaves that made Figure 11.13 traveled through nearly empty space for 14 billion years before entering the microwave detectors that created this map. You are looking at the image of the earliest light in the universe, a 14-billion-year-old "fossil."

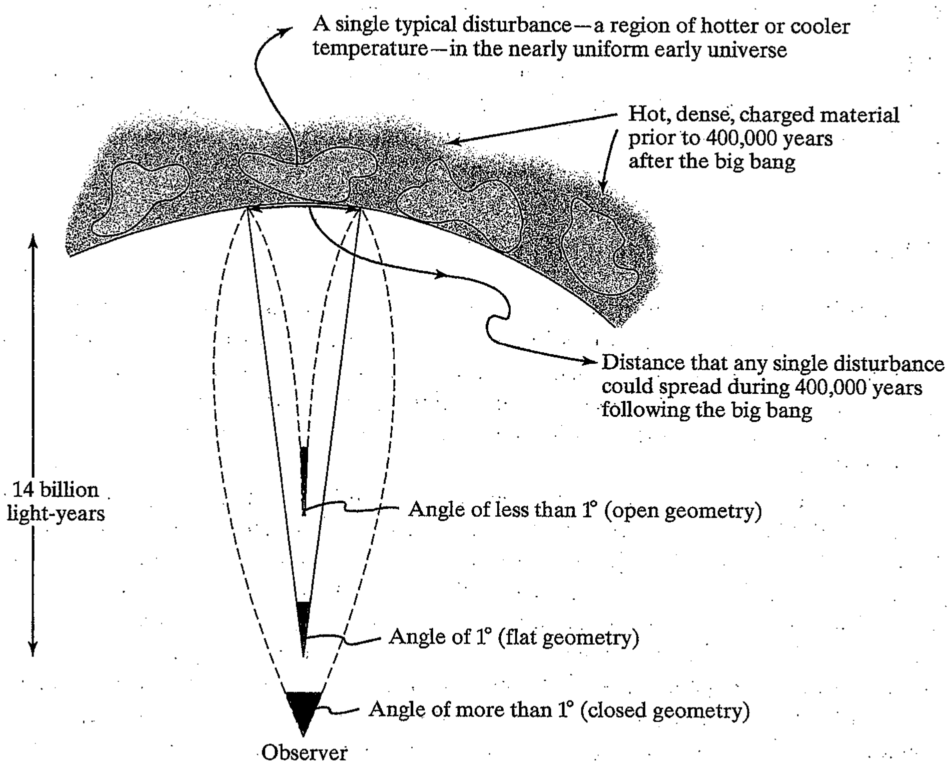
From this map, showing details of the waves of matter and energy (similar to sound waves in air) that sloshed around in the early universe, scientists conclude that the large-scale geometry of the universe is flat rather than closed or open (Figure 11.15). Here's how we know.

**How do we know the shape of the universe?** With their knowledge of the physical nature of the hot, dense, and electrically charged early universe, scientists can predict the maximum distance that wavelike disturbances in this material could travel during the 400,000 years between the big bang and the release of the light seen in this map. Astronomers can also directly observe this distance in the cosmic microwave background, based on the average size of the observed hot or cool regions seen in the map (**Figure 11.16**). However, such observations are distorted by the geometry of the space through which the microwave radiation travels on its long journey to Earth, and this distortion enabled scientists to determine that geometry. As shown in Figure 11.16, a typical wavelike disturbance, as observed today from Earth, should make an angle of about 1° if the universe is flat, while a closed universe would warp the radiation into an angle larger than 1° and an open universe would warp it into an angle smaller than 1°. The observed angle was about 1°—fairly conclusive evidence that the overall geometry of the universe is flat or at least very close to it.

> If you're religious, it's like looking at God.
>
> George Smoot, Leader of the Team That Announced in 1992 the Discovery of the Ripples in the Cosmic Microwave Background

CONCEPT CHECK 5 Since there is evidence that the universe is flat, does this mean that there is no such thing as curved or warped space? Defend your answer. (a) Yes. (b) No.

**Figure 11.16**
A typical wavelike disturbance in the material of the early universe, as observed today from Earth, should make an angle of about 1° if the universe is flat. A closed universe would warp the radiation into an angle larger than 1°, while an open universe would warp it into an angle smaller than 1°. The observed angle was about 1°—strong evidence that the overall geometry is flat.



## 11.5 DARK MATTER

We're accustomed to thinking that the universe is made mostly of the visibly luminous (shining) stars and a few nonluminous objects such as planets. But we've learned during the past 20 years that the universe is made of many more kinds of things than this. First, an enormous amount of the hydrogen and helium created in the big bang has neither gathered into stars nor collected within the visible galaxies but instead lies in the vast regions between the galaxies where it is invisible and nearly undetectable. Astronomers first detected it by observing how the light traveling to Earth from distant objects is partly absorbed as it passes through intergalactic space. The mass of this invisible intergalactic gas is now known to be 10 times larger than the mass of all the stars, planets, and luminous gas in the universe!

Stars, planets, and intergalactic gas are made of atoms of ordinary matter, just like your chair. But there are other kinds of matter, matter that is not formed into atoms. One example is the neutrino (see the neutrino telescope in Figure 1.2(d), also "How Do We Know?" in Section 6.5). There are a vast number of individual neutrinos flying through the universe with a total mass estimated at one-quarter of the total mass of all the stars. Another kind of nonatomic matter is the black hole (Chapter 5). Judging from what's known about the massive black holes at the centers of galaxies, these are estimated to contribute a total mass about one-tenth as large as the mass of all the stars.

That's pretty fantastic, in my opinion. But there's more. During the past few decades, scientists have learned that there is another kind of matter, matter not made of protons, neutrons, electrons, neutrinos, or any of the other particles currently known. Nobody knows what it's made of, although there are several hypotheses. It doesn't interact with electromagnetic radiation, so it can't be detected by emitted light (like stars) or reflected light (like planets) or absorbed light (like intergalactic gas), and nobody has yet detected it in the laboratory. But we know it's there because of its gravitational effects on the stars in galaxies, and we know there's a lot of it. The total mass of this so-called **dark matter** is 60 times larger than the mass of all the stars!

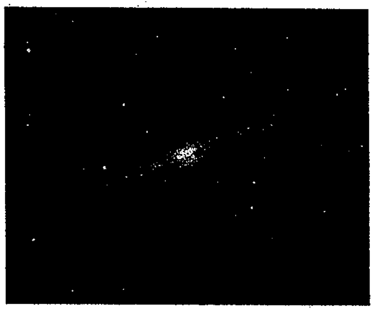


**Figure 11.17**
A galaxy, full of stars and gas and dust, viewed "edge on" (compare with the galaxy in Figure 1.23).

**Figure 11.18**
Vera Rubin. She made pioneering discoveries that contributed to understanding the existence and amount of dark matter by observing frequency shifts of stars in galaxies.

**How do we know that dark matter exists?** Several independent methods of observation show that most galaxies, including our own, are made mostly of dark matter. One method is based on the fact that galaxies are rotating structures, with stars and gas orbiting the center. Like planets orbiting the sun, the stars and gas are held into their roughly circular orbits by the gravitational pull of the massive center of the galaxy. When astronomers observe stars and gas clouds orbiting the centers of their galaxies, their speeds turn out to be so high that the galaxies would fly apart unless held together by the gravitational pull of many times more matter than we actually see. So galaxies must contain invisible matter.

But how can astronomers measure orbital speeds around distant galaxies where it's difficult to pick out individual stars let alone measure their speeds? Looking at galaxies that could be seen "edge on" (**Figure 11.17**) from Earth, Vera Rubin (**Figure 11.18**) compared the light coming from points on one side of the galaxy's bright center with the light coming from points on the other side. Since the galaxy is rotating, the stars on one side were moving toward Rubin's telescope, and the stars on the other side were moving away. The frequency of the light coming from the stars moving toward the telescope was higher than the frequency of the light moving away, for the same reason a police siren shifts to a higher pitch as the police car approaches you and then to a lower pitch as it recedes from you while you listen from the sidewalk. From the difference between the two frequencies, Rubin was able to calculate the speeds of the stars.

In a second method of observation, light reaching Earth from distant galaxies is warped as it passes through the gravitational fields of galaxies that lie in the path of the light. By analyzing this bending, called "gravitational lensing" (**Figure 11.19**), astronomers can deduce that the intervening galaxies contain far more matter than can be seen.

By the time you read these words, dark matter might be discovered in the laboratory. The biggest particle accelerator (Chapter 17) in history is coming online in 2009 or 2010 at the European Organization for Nuclear Research, or "CERN," near Geneva, and physicists believe that it will be able to spot the predicted candidates for dark matter, if they exist.

**Figure 11.19**
Warped light. To make this photograph, the Hubble Space Telescope peered straight through the center of a distant cluster of galaxies. The rounded objects in the photo are galaxies in this cluster. The stretched-looking objects are other galaxies lying at great distances behind the "foreground" cluster of galaxies. The light from these more distant galaxies is gravitationally warped as it passes through the foreground cluster. The warped light in this photograph comes from galaxies lying many billions of light-years away; some of this light originated when the universe was barely a quarter of its present age! A photograph such as this is direct visual evidence for the general theory of relativity.

From such observations, we know that our galaxy, and most other galaxies, is immersed in a giant spherical cloud of dark matter whose diameter is many times the diameter of the visible galaxy (**Figure 11.20**).

What, then, is this dark matter? No known form of matter can account for it. Scientists expect that entirely new forms of matter will be discovered, and there have been several theoretical suggestions about what form it might take. It must interact only weakly with ordinary matter, or we would have discovered it by now. Whatever it is, it's all around us: There are probably billions of dark matter particles passing through your body every second, but leaving no effect on your body. Dark matter has inspired many searches among cosmic rays (particles from space) and in high-energy physics experiments. A parallel situation existed during 1914 to 1955 (see "How Do We Know?" in Section 6.5) when theory suggested that an unobserved particle was created during beta-decay, but no such particle could be detected until 1955, when physicists discovered the neutrino. The laboratory discovery of dark matter would be momentous.

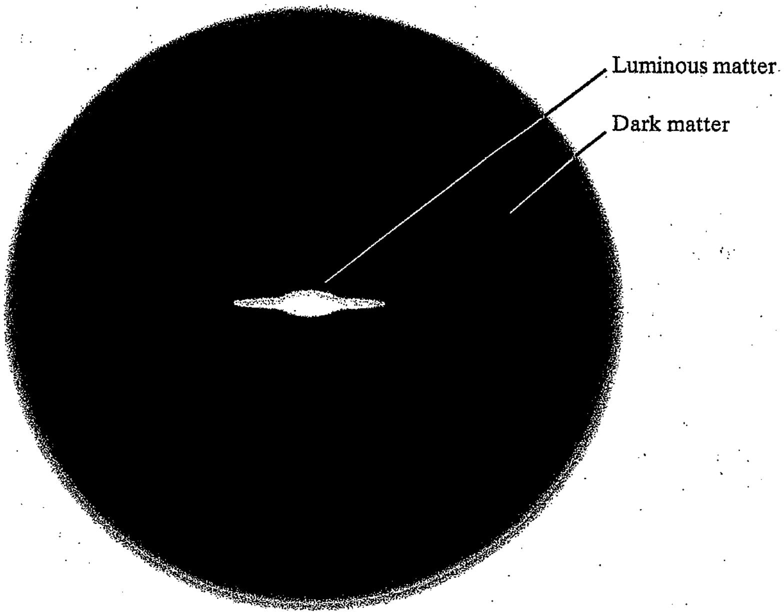


**Figure 11.20**
Dark matter forms a giant invisible spherical "cloud" around each visible galaxy. The small object at the center of the figure is a spiral galaxy, like our Milky Way galaxy, seen edge-on (compare Figure 11.17).

CONCEPT CHECK 6 What's so unusual about dark matter? (a) It exerts no gravitational force. (b) Its gravitational force pushes (or repels) instead of pulling. (c) It is made of material that has never been observed in our laboratories. (d) It moves faster than lightspeed. (e) It does not interact with electromagnetic radiation.

## 11.6 THE ACCELERATING UNIVERSE AND DARK ENERGY

Will the universe expand forever, or will it eventually collapse back inward on itself? This is similar to asking what happens to an object that is thrown upward from Earth's surface. If you throw a ball upward, it slows as it comes to a momentary stop at its maximum height and then immediately accelerates downward to the ground. But if NASA "throws" a space vehicle upward faster than 11 km/s (25,000 mph), it slows as it rises but instead of returning to the ground it keeps rising and escapes from Earth.

> Not only are we not at the center of the universe, we aren't even made of the same stuff the universe is.
>
> Joel Primack, Astrophysical Theorist, University of California

Like the rising ball and the space vehicle, it stands to reason that the universe's expansion should be slowing down. Just as the ball and the space vehicle are slowed by the backward pull of Earth's gravity, the universe's expansion should be slowed by the inward gravitational pull of all the matter in the universe. It's important to quantitatively measure this deacceleration of the universe, because a sufficiently large deacceleration would imply that the universe is like the upward-thrown ball in that it will eventually stop expanding and then immediately begin collapsing on itself in an ultimate "big crunch." On the other hand, if the deacceleration is sufficiently small, then the universe is like the upward-thrown space vehicle and will continue expanding forever. But it's difficult enough to measure the expansion rate of the universe, let alone the rate at which that expansion rate is slowing down, so for many decades cosmologists didn't know whether the universe would eventually collapse or would continue expanding forever.

During the 1990s, cosmologists managed to measure that deacceleration. The result, in 1998, was a shocker: The universe's expansion isn't slowing at all. It's speeding up.

**How do we know the universe is accelerating?** First, let's see how scientists measure the speeds at which the galaxies are moving apart. Light waves stretch as they travel through the universe, because of the stretching of space during the time of travel. Thus, light from distant galaxies arrives at Earth with a longer wavelength than it had when it left its home galaxy; it is shifted toward the long wavelength or red end of the electromagnetic spectrum. This **redshift** of the light from distant galaxies, first discovered during the 1920s, was the earliest evidence of the big bang and the expansion of the universe. Scientists can measure the amount by which a galaxy's light is redshifted and from this deduce the galaxy's speed.

But in order to use redshifts to confirm that the universe is expanding, one needs to know that it actually is the more distant galaxies that are redshifted the most. Such distances are not easy to determine. You can't just stretch a tape measure out to a distant galaxy! Nevertheless, astronomers have for many years had methods for determining such distances and have amply confirmed that more distant galaxies are more redshifted in just the way expected in an expanding universe.

Recently, astronomers developed an especially powerful method of determining such distances, along with speeds. Large modern telescopes can detect a particular type of supernova explosion (an explosion of a star, Section 5.4) in far-distant galaxies. These "Type 1a supernovas" are bright enough to be seen even at distances greater than halfway across the observable universe. Also, it's known that all Type 1a supernovas are nearly identical, and all shine with the same brightness during their roughly one-month period of maximum intensity following the explosion. Since they all have the same actual brightness, more distant ones always appear dimmer from Earth, and from their observed brightness one can deduce how far away they must be. Thus, Type 1a supernovas are our most accurate markers for determining expansion speeds and distances across most of the universe. They're sufficiently accurate to determine not only the speeds but also the rate of change of the speeds—the accelerations—of distant parts of the universe.

In 1998, these observations revealed that the expansion of the universe is actually speeding up.

This was not expected. If you threw a silver dollar up into the air and, instead of slowing and coming back down, it sped up until it rose out of sight, you'd say that's a pretty mysterious way to lose a dollar. You'd probably want to know what pushed it into outer space. In the same way, the gravitational pull of all the matter in the universe should slow the universe's expansion. But it's speeding up. What's pushing on it?

Recall that the receding galaxies are not really moving at all, but are simply remaining roughly at rest in space while space itself expands, like the raisins in our expanding balloon analogy in Section 11.3. Since accelerations are caused by forces, the accelerating expansion means that something is pushing outward on the fabric of space. What can it be? It's certainly not matter of either the ordinary or the dark type, because the force of gravity from both ordinary and dark matter can only pull, not push. Scientists believe that all of space, including even "empty" space or vacuum, must contain some new form of nonmaterial energy that pushes outward. It's called **dark energy.**

This astonishing new concept burst upon the physics community in 1998 with the discovery of the acceleration of the universe. Nobody knows what dark energy is, although some theories relate it to the energy of the field that "inflated" the universe during the early moments of the big bang (next section). Dark energy is more mysterious than dark matter: We have evidence that it's there, but little idea what it is.

Dark energy must influence the shape of the universe, because Einstein says that all forms of energy have mass and because mass affects the curvature of space. It happens that it's possible to infer the amount of dark energy present in the universe from the details of the cosmic microwave background. When the mass of this dark energy is added to the masses of the luminous matter, nonluminous ordinary matter, and dark matter in the universe, the total comes out to be precisely the amount needed to flatten the overall geometry of the universe! Thus, the flatness of the universe, dark matter, the acceleration of the universe, and dark energy all fit together in a beautifully consistent but totally unexpected picture of the universe.

All of this provides a new answer to the ancient question "What is the universe made of?" Observations of the cosmic microwave background, and of the universe's acceleration show that it's made mostly of dark energy! The other ingredient is matter, the great bulk of which is dark matter. In more detail, the universe is 73% dark energy, 23% dark matter, nearly 4% nonluminous "ordinary" matter (including intergalactic gas, neutrinos, and black holes), and only 0.4% (less than half a percent) ordinary visible matter (**Figure 11.21**). The universe is stranger than you or I could have imagined: 96% of it is made of completely unknown matter and energy, most of the remaining 4% is invisible, and only a fraction of 1% is normal visible matter. The universe we can see is only a tiny fraction of all that is!

To return to the question that began this section: If the universe continues its accerating expansion, it will not only expand forever but will expand faster and faster forever. But this assumes that the universe does keep accelerating, and, given the surprises of the past few years, few cosmologists would bet much on any particular long-term scenario.

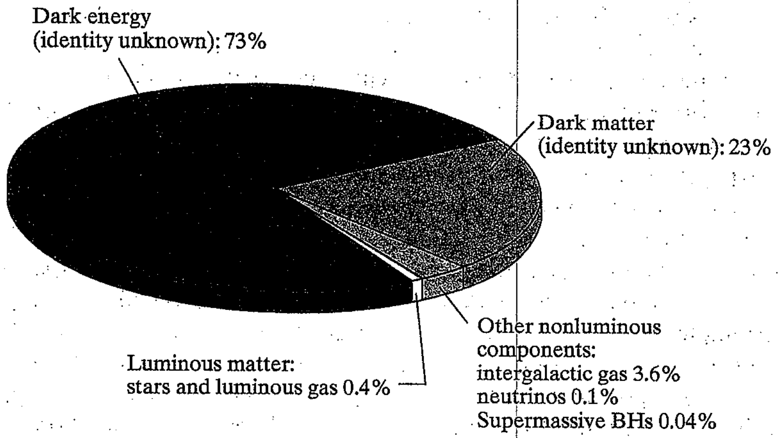


**Figure 11.21** What is the universe made of? These numbers show that, whatever may be the nature of the unknown dark energy and dark matter, the universe is not made primarily of the same stuff that we are made of!

**▶ CONCEPT CHECK 7** Type 1a supernova explosions make excellent markers for measuring the universe's acceleration because (a) they all emit about the same amount of light; (b) they are all the same distance away from us; (c) they can be seen from immense distances; (d) they are all moving away from us at the same speed.

**▶ CONCEPT CHECK 8** Dark energy (a) is made of some unknown form of matter; (b) has mass; (c) is made of invisible electromagnetic radiation; (d) pushes on space.

## 11.7 COSMIC INFLATION AND A BRIEF HISTORY OF THE UNIVERSE

Alan Guth (**Figure 11.22**) bicycled hurriedly to the Stanford Linear Accelerator Laboratory (SLAC) to start work on the morning of December 7, 1979, breaking his personal speed record with a time of 9 minutes and 32 seconds. Working late the previous night, he had begun to understand a new and extraordinary cosmological phenomenon, and he was anxious to get back to thinking about it. He checked his calculations from the night before and found them exactly on target. Several weeks later the young physicist apprehensively presented his new idea to a packed audience at SLAC. The response was overwhelmingly favorable, exceeding Guth's wildest expectations. The hypothesis of **cosmic inflation** was born.

Guth had combined ideas from general relativity, quantum physics, and high-energy physics to explain how the matter and energy in the universe could have been created from nearly nothing by a high-energy submicroscopic event occurring in nearly empty space. Guth's hypothesis does not explain how the universe actually got started, but it does explain how, starting from a tiny fragment of spacetime containing a minuscule amount of matter and energy, the universe expanded enormously while filling with matter and energy.

Briefly, Guth's hypothesis says that the universe started out unimaginably small, far smaller than a proton, and immediately expanded. Very early, at a trillionth of a trillionth of a trillionth (!) of a second after the beginning, the universe experienced an even more rapid period of expansion at speeds greatly *exceeding* lightspeed, during which it stretched by a factor of $10^{25}$ during only $10^{-35}$ seconds. To see how mind-boggling this is, try writing out these two numbers. This breakneck expansion is called, appropriately, "inflation" (recall Figure 11.14).

**Figure 11.22** In 1979, high-energy particle physicist Alan Guth made a monumental cosmological discovery: the idea of cosmic inflation. The hypothesis has significant experimental support in satellite observations of the cosmic background radiation and in other cosmological observations. Cosmic inflation is the best scientific explanation to date of the details of the first few moments of time.

Nowhere is the inherent unity of science better illustrated than in the interplay between cosmology, the study of the largest things in the universe, and particle physics, the study of the smallest things.

Rocky Kolb, Physicist at Fermilab

This sounds pretty bizarre, but it's been receiving some observational confirmation lately. One response to this hypothesis is "How can the universe expand at faster than lightspeed, since special relativity predicts that nothing goes faster than light?" We've already dealt with this in Section 11.3: Special relativity predicts that no object can *move through space* faster than light. But general relativity tells us that the expansion of the universe is an expansion of the fabric of space itself, and there is no speed limit on this. The expansion carries galaxies and other objects along with it while those objects remain at rest relative to the space around them.

According to Guth's hypothesis, our universe started out so small that quantum effects such as the uncertainty principle (Chapter 13) dominated. One implication of this principle is that in every region of space, the energy in the region fluctuates randomly (or unpredictably) up and down around its average value, a little like the surface of a small portion of a lake fluctuates up and down due to wind rippling its surface. Even in supposedly "empty" space, such energy fluctuations are still required by the uncertainty principle.

At extreme submicroscopic sizes, it's thought that space and time do not exist as we know them but are instead broken up or "quantized" into tiny separate fragments having durations of about $10^{-49}$ s (that's *short*!) and diameters of about $10^{-35}$ m (that's *small*!). According to the inflation hypothesis, an unusually large energy fluctuation occurred in just such a fragment. This fluctuation had an energy of only some $10^9$ joules, about the energy of one automobile tank of gasoline. According to $E = mc^2$, the mass of this much energy is 0.01 milligrams—about as massive as a grain of dust. This doesn't sound like enough energy to start a universe, but amazing things can happen when it's all crammed into such a tiny region. One of those amazing things was that so much energy in such a small region created an enormous temperature of some $10^{32}$ degrees (try writing it out). Our universe immediately began expanding simply because it was so hot (this is also the reason ordinary explosions expand), and the expansion cooled it from its initial $10^{32}$ degrees down to around $10^{28}$ degrees.

Where the telescope ends, the microscope begins. Which of the two has the grander view?

Victor Hugo

A major theme of modern physics, already encountered in our discussion of gravitational and electromagnetic fields (Chapter 8), is that the universe is made of just a few kinds of fields that extend throughout all space and time. The cosmic inflation hypothesis is based on a new type of field, not yet observed in nature, called the inflation field (Chapter 17). When our then-tiny universe had expanded and cooled to $10^{28}$ degrees, the inflation field developed something called a "false vacuum" that amounts to a gravitational force that strongly *repels* instead of attracting like the gravity that we know. This repulsive force sent the universe into a brief period of rapidly accelerating expansion or "inflation" up to speeds far faster than lightspeed. The expansion was actually "exponential"—that is, it had a fixed doubling time (see Section 7.8). Exponential growth can be surprising. Although this inflationary period began at $10^{-36}$ s into the big bang and lasted only until $10^{-34}$ s into the big bang, the universe's size doubled nearly 100 times, resulting in a universe that was about $10^{25}$ (10 trillion trillion) times larger than it was before inflation. Even after inflation our universe was only a millimeter across but nevertheless the expansion was enormous. Think of a balloon being filled by a fire hose.

Physicists believe that there are just four types of fundamental force fields: the gravitational field, electromagnetic field, "weak force" field, and "strong force" field. The last two are apparent only at the level of the atomic nucleus, in connection with nuclear forces (Chapters 14 and 15). But in the fires of the early universe, the four fundamental forces were all "melted together" and indistinguishable. There was only one force, not four. Physicists say that the four forces had the same "symmetries" and so did not exist individually. As the universe cooled, the gravitational force suddenly "froze out" of the unified force; it lost the symmetry that had unified it with the other forces and took on its own distinctive gravitational properties. This "symmetry breaking" is analogous to the loss of symmetry when water freezes: All directions are equivalent inside water, but ice crystals line up in specific directions—a loss of symmetry. As the universe continued cooling, the strong force froze out and formed its own unique patterns such as the quark-gluon plasma simulated in **Figure 11.23**. Finally, the weak force and the electromagnetic force froze out also, leaving us with the four forces that have their four distinct sets of properties that we observe today.

But where did all the mass and energy in the universe come from, if energy is conserved and if everything developed from an energy fluctuation having the mass of a dust grain? Here's where: The gravitational energy of any isolated lump of matter such as a star, that is held together only by gravity, is *negative* (less than zero), because work *must be done on* (rather than *can be gotten from*) the star in order to pull it apart into separated pieces. In the same way, the gravitational energy of the entire universe, due to the attraction between all its parts, is *enormously* negative. Inflation didn't alter the universe's net energy, but instead created negative energy (gravitational) and positive energy (kinetic, radiant, and the energy needed to create matter) in equal amounts. It's like a man who spends a lot of money by going into debt; he spends like a millionaire, but his net financial balance remains zero. Thus the universe's net energy remains very close to zero, balanced between an enormous negative gravitational energy and a slightly more enormous (by one gasoline tank) positive energy. The positive energy of matter and motion that you see today was scavenged in the early universe from gravity.

> It is said that there's no such thing as a free lunch. But the universe is the ultimate free lunch.
>
> **Alan Guth, Originator of the "Inflation" Idea That Explains How the Big Bang Could Have Created Our Universe out of a Vacuum**

As Alan Guth puts it, cosmic inflation is "the ultimate free lunch": That gasoline tank's worth of energy was the seed for everything. It's a powerful story of how things came to be.

**Figure 11.24** shows some of the details of the time sequence. The time line is plotted in powers of 10, rather than simply in seconds, because a lot happens fast in the early universe due to the high energies involved!

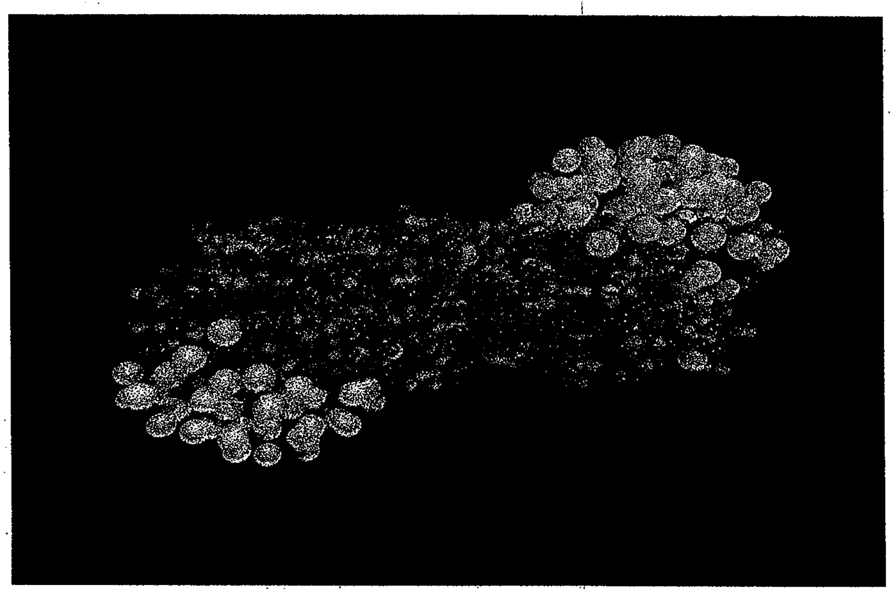


**Figure 11.23**
Simulated "snapshot" of two lead nuclei colliding at very high energy. The simulation portrays the nuclei just $6 \times 10^{-24}$ seconds after impact, showing protons and neutrons in white. The smaller particles portrayed in darker hues are "quarks," the particles of which protons and neutrons are made (see Chapter 17). This is a simulation of a real experiment that reproduced the theoretically predicted "quark plasma" that is believed to have existed at 10 microseconds after the big bang.

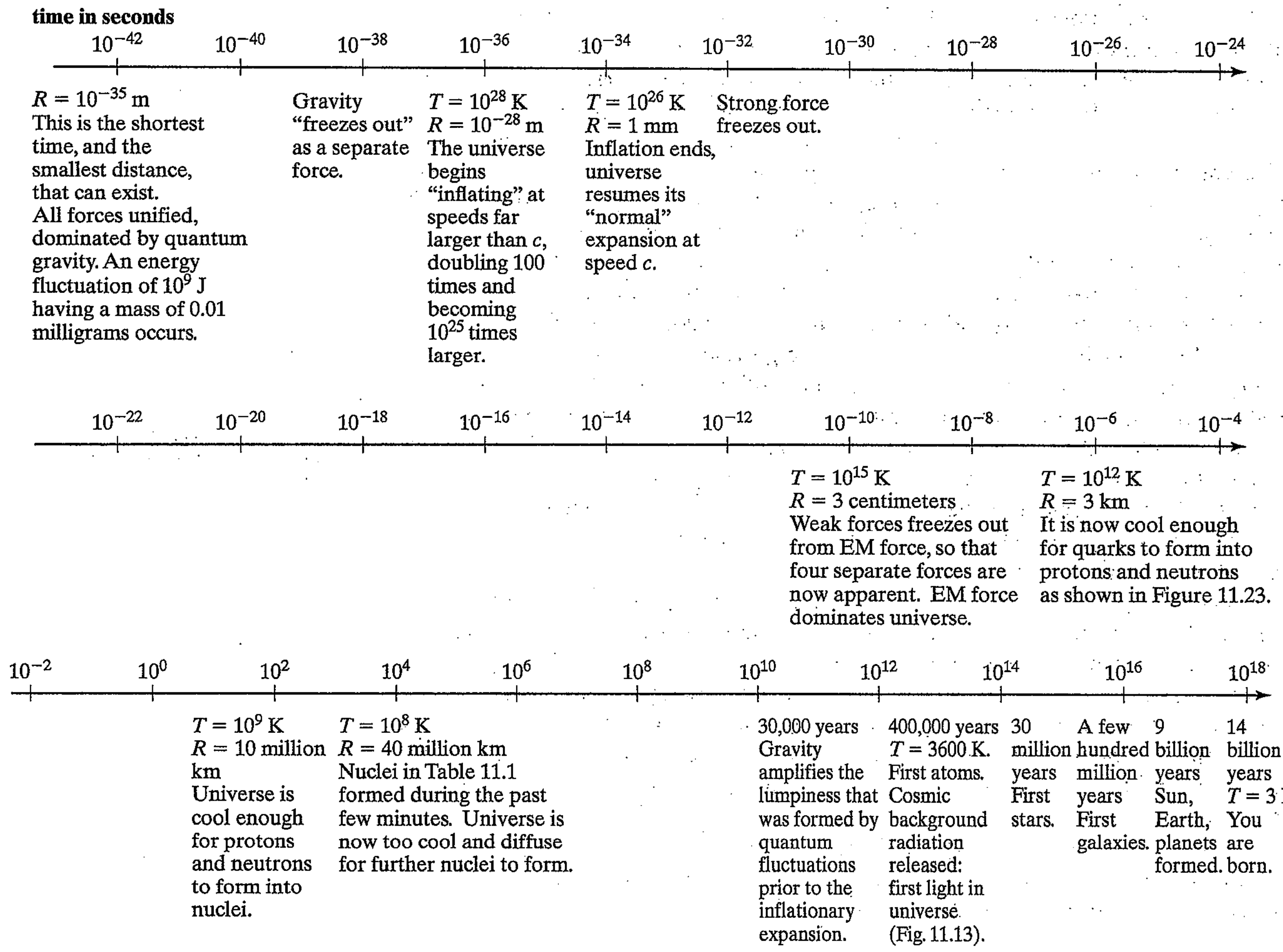


**Figure 11.24**

A really brief history of the universe. All numbers are only approximate, and the first millionth of a second is hypothetical (not yet checked directly by observation)! Temperatures are in degrees above absolute zero, or Kelvins, abbreviated K. The radius of the observable universe is abbreviated as R. For all times after the end of inflation, the universe is $10^{25}$ (10 trillion trillion) times larger than the *observable* universe, because the universe expanded far faster than lightspeed during inflation so that nearly all of it is so far away that light cannot reach here from there during the entire history of the universe.

**How do we know that cosmic inflation occurred?** Cosmic inflation has already passed several observational tests. First, it provides a convincing explanation of the origin of the large-scale gathering or "clumping" of stars into galaxies, of galaxies into clusters of galaxies, and even of clusters into superclusters, seen in today's universe. It's not hard to understand how any initial lumpiness would be amplified by gravitational forces into today's quite "lumpy" universe of stars and galaxies—just as gravity can create stars out of diffuse clouds of gas and dust (Chapter 5). But prior to the inflationary hypothesis, the big bang model offered no clue as to what created the initial lumpiness. Cosmic inflation's answer is that quantum uncertainties during the big bang caused microscopic lumps that were then stretched by the expansion of the universe. Without inflation, the amount of stretching would be far too small for quantum fluctuations to explain the vast lumps (clusters of galaxies, etc.) seen today. Inflation resolves this problem: Inflationary expansion stretches the initial quantum lumps enormously, and gravity works on these stretched lumps to produce precisely the clumping observed today.

Second, Guth's hypothesis predicts and explains the observed flatness of our universe. The reason is simple: Inflationary expansion plus additional "normal" expansion since that time stretched the universe so hugely that any overall curvature is now stretched flat, the way that the surface of an expanding balloon gets flatter and flatter as perceived by an ant on the balloon's surface. It's surprising that our universe should be flat, because a flat universe represents a delicate balance right at the borderline between the finite closed geometry and the infinite open geometry of Figure 11.15. Without inflation, there is no convincing explanation for why the universe should be so delicately poised. Guth predicted a flat universe more than a decade before the first observation, in 1992, of the patterns in the cosmic microwave background suggested that the universe really is flat. In 2001, more accurate observations of these patterns provided further confirmation of Guth's prediction.

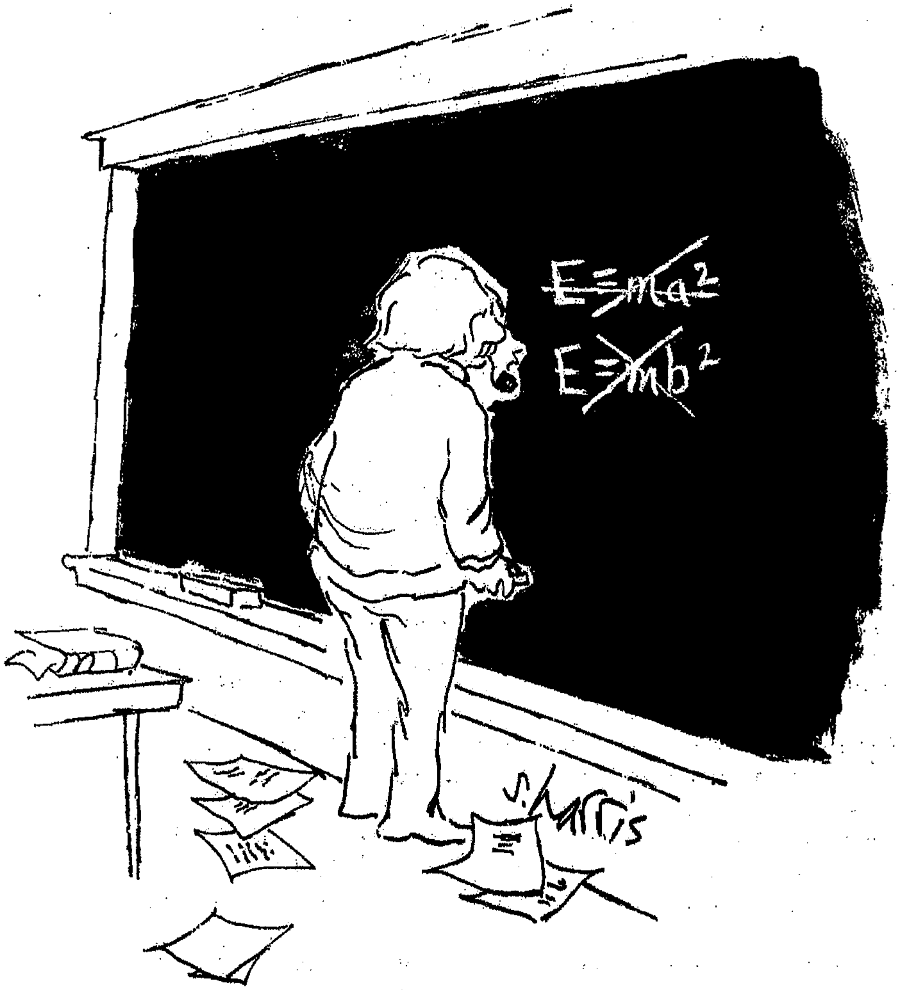
It appears that, without initial energy fluctuations and inflation, our universe could not have developed the patterns seen today in the layout of the galaxies. The great clusters of galaxies stretching across the universe still retain the microscopic pattern of those initial quantum fluctuations occurring in an unimaginably tiny lump of energy that started all of this. It all sounds too amazing to be true, but the truly amazing thing is that it's been checked in some detail by specific observations.

Just as ice crystals freeze along a direction that is previously undetermined or random, so cosmic inflation predicts that the specific "direction" in which the inflation field "froze" during the big bang was also random. But when I speak of "different directions" of inflation-field freezing, I really mean different properties of the various fundamental forces as they froze out of the preexisting symmetric unified force. In this process, *basic properties of our universe such as the masses and charges of the fundamental particles might have been determined randomly*. It's even possible that ours is just one of many universes created in similar processes, each born in a new toss of the quantum dice and each characterized by different physical properties.

According to the inflationary view, it's possible that in our universe the numbers turned out to have just those values that allowed intelligent animals to evolve. In any other universe, in which these numbers were very different, life and intelligence might have been physically impossible. Our own existence might turn out to be the best explanation we have for these numbers having the values that they do have. This idea, that our universe must be organized in the way that it is because any other organization would not allow intelligent beings to be here to ask the question in the first place, is called the **anthropic principle.**

And this outrageous but plausible connection between the big bang and our lives on Earth is a good place to end our excursion into cosmology.

▶ CONCEPT CHECK 9 Can anything go faster than light? (a) Yes, space can expand at faster than lightspeed. (b) Yes, certain subatomic particles can move through space at faster than lightspeed. (c) No, special relativity forbids it. (d) No, general relativity forbids it.



Answers to Concept Checks and odd-numbered Conceptual Exercises and Problems can be found in the back of the book.

## Review Questions

### EINSTEIN'S GRAVITY: THE GENERAL THEORY OF RELATIVITY

1. List two experiments you could do in a spaceship accelerating at $1g$ through outer space that might make you think you are at rest on Earth.
2. According to the equivalence principle, to what is acceleration equivalent?
3. In your own words, state the equivalence principle.
4. Give one piece of evidence showing that gravity bends light.
5. As observed in an accelerating reference frame, does a light beam bend? What does this tell us about the effect of gravity on light beams?
6. According to Newton, gravity is a force exerted by material objects on other material objects. What is gravity according to Einstein?

### THE BIG BANG

7. About how old is the universe?
8. Describe two different pieces of evidence supporting the big bang.
9. Of what element is the universe mostly made?

10. Following up on the preceding question, what is the second most prevalent element in the universe?
11. Name two elements that were not made in the big bang. Name two that were.

### THE GEOMETRY OF THE UNIVERSE

12. Give an example of a flat two-dimensional space, a curved two-dimensional space, and a two-dimensional space of finite extent.
13. How might we tell from inside our actual three-dimensional space whether space is curved?
14. List the three possible large-scale geometries of the universe, and describe at least two of them.
15. In what fundamental way does the big bang differ from an ordinary explosion?
16. Due to the expansion of the universe, are the galaxies moving through space? Explain.

### THE SHAPE OF THE UNIVERSE

17. What does the evidence tell us about the overall shape of the universe?
18. List one piece of evidence showing that we live in a flat universe.
19. What is the cosmic microwave background?
20. The big bang emitted lots of high-energy radiation. So why do we detect the big bang radiation primarily as low-energy microwaves?

### DARK MATTER

21. Roughly what percentage of the universe's total mass is made of ordinary matter?
22. Roughly what percentage of the universe's total mass is made of dark matter?
23. What is "dark matter"?
24. Why is it called "dark" matter?
25. What led astronomers to hypothesize the existence of dark matter?

### THE ACCELERATING UNIVERSE AND DARK ENERGY

26. Is the universe's expansion slowing down, speeding up, or maintaining an unchanging speed?
27. Describe the observations that show that the universe is accelerating.
28. What is causing the universe's expansion to speed up?
29. Roughly what percentage of the universe is made of dark energy?

### COSMIC INFLATION AND A BRIEF HISTORY OF THE UNIVERSE

30. What does the cosmic inflation hypothesis try to explain?
31. According to the cosmic inflation hypothesis, what started the big bang?
32. Why do they call it "inflation"?
33. Since energy is conserved, and since the universe started from only a gasoline tank's worth of energy, having a mass of only 0.01 milligrams, how can the universe have possibly attained the enormous amount of energy and mass that it has today?
34. Give two pieces of evidence supporting the hypothesis of cosmic inflation.

## Conceptual Exercises

### EINSTEIN'S GRAVITY: THE GENERAL THEORY OF RELATIVITY

1. If you were in a rocket ship in space (far from all planets and stars) accelerating at $2g$, how heavy would you feel?
2. In the preceding question, what if your acceleration were instead $0.5g$? What if you were not accelerating at all?
3. In what way is the general theory of relativity more "general" than the special theory of relativity?
4. Astronauts' hearts and muscles weaken in space due to the prolonged weightlessness. How might artificial gravity be installed in a space station to deal with this problem?
5. If you were in a rocket ship in space (far from all planets and stars) accelerating at $2g$ and you dropped a ball, how would it move as observed by you?
6. In the preceding question, what if your acceleration were instead $0.5g$? What if you were not accelerating at all?
7. In the equivalence principle, what is equivalent to what?
8. Why don't we notice the gravitational bending of light on Earth?
9. Does a high-speed bullet's path bend more than a light beam bends? Why?
10. A rifle barrel and a laser both point directly toward a target some distance away. General relativity says that the bullet and the light beam both experience the same downward acceleration during their horizontal travel, yet the bullet hits the target well below the laser beam. Explain.

### THE BIG BANG

11. Where did your body's hydrogen nuclei originate?
12. Did your body's oxygen nuclei originate in the big bang?
13. The big bang has been described as the place where cosmology meets submicroscopic physics. Why?
14. The big bang created just three chemical elements. Why didn't it create more?
15. Suppose we could instantly reverse the expansion of the universe so that it becomes a contraction. If we then observed distant galaxies, how would they appear?
16. Is there a specific place in the present-day universe where the big bang happened? Explain.

### THE GEOMETRY OF THE UNIVERSE

17. If we consider Earth's surface to be a two-dimensional "space," the equator is one "straightest possible line" in this space. Are there other such lines?
18. On Earth's surface, are the north-south lines of longitude among the straightest possible lines? What about the east-west lines of latitude?
19. If you draw a triangle on the surface of a sphere, the sum of its angles is greater than 180°. Is it possible to draw a triangle on the surface of a sphere for which each angle is 90 degrees so that the sum of the three angles is 270 degrees? Explain.
20. Is there a place in the present-day universe that is the center of the universe? Explain.
21. Are there places in the present-day universe that are at the edge of the universe? Explain.

## THE SHAPE OF THE UNIVERSE

22. What important event happened at about 400,000 years after the big bang?
23. About 400,000 years after the big bang, the cosmic background radiation was released. How did the universe after this event differ from the universe before this event?
24. Imagine a huge triangle stretching across a large portion of the observable universe. Will the three angles of this triangle add up to the usual 180°, or will they add up to more than, or less than, 180°?
25. If a living observer could have been there to observe the universe only 300,000 years after the big bang, would they have seen anything? Explain.
26. Why couldn't light travel through the early universe?
27. What does it mean to say that the universe is "flat"?

## DARK MATTER

28. What evidence is there that our Milky Way galaxy might contain "dark" matter?
29. According to current theories, is there dark matter in your room?
30. Why can't you see the dark matter that is in your room?
31. Since dark matter is invisible, what leads us to think it might exist?
32. Why would the laboratory discovery of dark matter be momentous?
33. Does dark matter interact by means of the gravitational force? How do we know?

## THE ACCELERATING UNIVERSE AND DARK ENERGY

34. Since the universe is accelerating as it expands, is there any doubt among cosmologists that the fate of the universe is to expand forever? Explain.
35. Cosmologists did not expect to find that the universe is accelerating. What did they expect?
36. Why are type 1a supernovas such good markers for determining the rate of expansion of the universe?
37. What is the universe mostly made of?
38. Why do we think there is dark energy?
39. Suppose that a certain galaxy, galaxy X, is so far from our galaxy that the expansion of the universe causes it to move away from our galaxy at half of lightspeed. Does this mean that galaxy X is moving through space at half of lightspeed? Explain.

## COSMIC INFLATION AND A BRIEF HISTORY OF THE UNIVERSE

40. In what ways was the emergence of the four different fundamental forces during the big bang similar to the change of the state of water from liquid to solid?
41. If the theory of cosmic inflation is correct, then what is undoubtedly nature's single most important example of quantum uncertainties?
42. How could the large-scale structure we see in the universe today have originated from tiny quantum fluctuations?
43. Is the total gravitational energy of an isolated star positive, or negative, or zero? Defend your answer.
44. A huge amount of energy was needed to create all the matter and all the motion that we see in today's universe. According to the cosmic inflation hypothesis, where did it come from?
45. Cosmic inflation might sound far-fetched, but there is evidence for it. Describe two pieces of evidence.