GALAXIES

On any given night, as we look into the sky with modest-sized telescopes, we can see that the hazy band of the **Milky Way** is composed of countless millions of stars. Those stars appear as tiny pinpricks of light. But lots of other less distinct objects appear as fuzzy masses, too distant to resolve. Those cloudlike objects, called "nebulae," were the subject of intense debate in the early twentieth century.

The Nebula Debate

Some astronomers thought nebulae are nearby dust clouds that are illuminated by other stars. In that case, they would be fairly close by and have no resolvable structures, even using the most powerful telescope. Other astronomers suggested that nebulae are much more distant clusters of stars. They are composed of lots of individual stars, but are much too far away for those stars to be resolved.

This controversy came into sharp focus on April 26, 1920, when rival American astronomers Harlow Shapley and Heber D. Curtis engaged in a public debate at the National Academy of Sciences. The younger Shapley had come into prominence by discovering that the Milky Way is much larger than previously thought—more than 100,000 light-years across. Given that immense size, he couldn't imagine that much more distant objects existed. It's ironic that Shapley, who had dramatically increased the accepted size of the known universe, just couldn't accept how much larger the universe really is.

Curtis, on the other hand, argued that nebulae are much more distant collections of stars like our own. He saw the distinctive shapes of nebulae with spiral arms and central bulges, and concluded that a cloud wasn't likely to adopt that shape. However, Curtis believed Shapley was in error about the size of the Milky Way and actually thought the universe to be smaller than Shapley thought it is, so each man got something right and something wrong.

The more senior Curtis is said to have been the more eloquent of the two, and some attendees found him to have been more persuasive. But in science, debaters don't settle controversies. The scientific method demands that independently verifiable measurements and observations be the ultimate arbiter of any scientific question. The fact of the matter is that no one could make such observations with the tools available before 1920.

Distance and the Standard Candle

The basic problem was that astronomers were unable to tell how far away the nebulae are. This is actually a general problem in astronomy. We see the sky as a two-dimensional array, and there is no way of telling whether a star or nebula appears dim because it doesn't give off much light or because it is far away. An important tool that astronomers use to estimate distances—to supply that third dimension—is called the *standard candle*.

A standard candle is any object whose energy output is known. A 100-watt lightbulb, for example, is a splendid standard candle because we know exactly how much light it puts out each second. By comparing the known output of the standard candle to the amount of light we actually receive from it, we can tell how far away it is. We show an example of such a calculation at the end of this chapter.

Henrietta Swan Leavitt (1868–1921) headed the department of photographic stellar photometry at the Harvard College Observatory.

In astronomy, a fascinating type of star called a *Cepheid variable* is often used as a standard candle. These stars, the first of which was discovered in the constellation Cepheus, show a regular behavior of steady brightening and dimming over a period of weeks or months. Henrietta Leavitt (1868–1921) of Harvard College Observatory showed that the absolute magnitude (that is, the stars' luminosity) of these stars is related to the time it takes for them to go through the dimming-brightening-dimming sequence. Thus we can watch a Cepheid variable for a while and deduce how much energy it is pouring into space. This measurement, together with knowledge of how much energy we actually receive, tells us how far away it is.

Physics in the Making

The Women of Harvard Observatory

Edward Pickering became the director of the Harvard College Observatory in 1877. His mission, as he saw it, was to collect and categorize as many astronomical facts as possible. In particular, the observatory had piles of photographic plates of stellar spectra in its rooms, pictures of light taken from thousands upon thousands of stars. Pickering was chosen to administer a fund for creating a catalog of these spectra, which meant hiring people to carefully look over photographic plate after photographic plate and devise a system for categorizing them—a tedious task, indeed.

Pickering proceeded to hire a staff of all women assistants. Other astronomers joked about "Pickering's harem," but Pickering said he believed

Annie Jump Cannon (*foreground with magnifying glass*) and Henrietta Swan Leavitt (*sitting to the right of Cannon*) contributed important studies of the spectroscopy of stars at the Harvard College Observatory.

women were more suitable than men for this careful and repetitive work. What he did not say was that women worked for far less money than did men. They were paid 25–35 cents an hour for their work, which was actually a decent wage for women at that time. In addition, some women, including students, started to work at the observatory as unpaid volunteers so they could learn more about astronomy.

The *Henry Draper Catalogue* was published by the observatory in nine volumes, starting in 1918, and contained the spectra of 225,300 stars. But what was even more significant was the development of several women assistants into some of the most important contributors of their time to the progress of astronomy.

- Antonia Maury, a student of the first woman astronomer in the United States (Maria Mitchell), devised the first classification scheme for stars. Her work enabled later astronomers to develop the basic categories of stars, from white dwarf to red giant.
- Annie Jump Cannon developed the standard classification scheme for stellar spectra, from bright new stars to dying old ones. This sequence also turned out to be a guide to the temperatures and luminosities of stars.
- Henrietta Swan Leavitt discovered the relationship between period and luminosity of Cepheid variable stars, which became the standard candle that enabled later astronomers to measure distances to other galaxies.

It is no exaggeration to say that the work of these three women formed the foundation of modern astronomy.

Connection

Astronomical Distances

Miles and kilometers are not much use when trying to describe distances between stars or galaxies. It would be like trying to count the number of centimeters between New York and Boston. Instead, astronomers use distance units called the "light-year" and the *parsec.* What are these units? Is a light-year a unit of time or a unit of distance?

A light-year is not a unit of time but a unit of distance—the distance light travels in 1 year. You know that light travels very fast, at 300,000 km/s. If you do the math, you'll find out that a light-year turns out to be 9.46×10^{12} kilometers. (That's 10 trillion kilometers in round numbers.)

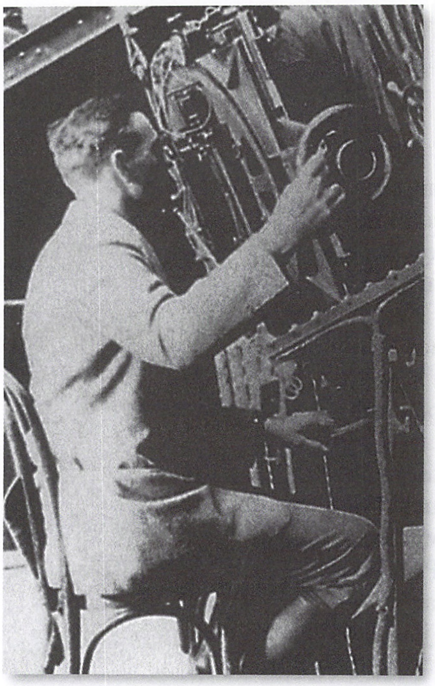
This may seem to you like a really enormous distance, and it is in terms of distances on Earth. But in terms of stars, even a light-year isn't that much. For example, the closest star to the Sun, called Proxima Centauri, is more than 4.2 light-years away. That means if a beam of light was emitted from Proxima Centauri when you graduated from high school, it wouldn't arrive on Earth until after you had graduated from a typical college program. And that's just the closest star, not the more distant ones.

When you start to consider galaxies, even light-years don't do the job. A typical galaxy such as the Milky Way is about 100,000 light-years across. Our nearest neighbor galaxy, called the Andromeda galaxy (located in the constellation Andromeda), is about 2.5 million light-years away. Astronomers use a base unit, the parsec, for these distances; a parsec equals 3.26 light years. Then they build on that unit and use kiloparsecs (kpc) and megaparsecs (Mpc), which equal 1000 and 1 million parsecs, respectively. Let's face it, the universe is a pretty big place! ●

Edwin Hubble and the Discovery of Galaxies

As so often happens in science, improved instruments were the key to discovery. In this case a larger telescope, quite literally, resolved the issue. In 1900 the world's largest telescopes were reflectors with mirrors in the range of 50 to 60 inches in diameter—not large enough to reveal nebular structure. However, the Carnegie Institution of Washington decided to build a mammoth new telescope with a mirror that was an unprecedented 100 inches in diameter on Mount Wilson, near Los Angeles, California. At the time, Mount Wilson was a lonely outpost on the outskirts of a small city. Today the Los Angeles metropolitan area has almost engulfed it, but in those days it afforded astronomers a chance to look at the sky through clear, unpolluted air.

In 1919, the young American astronomer Edwin Hubble (1889–1953), fresh from distinguished service in the First World War, went to work at Mount Wilson and used this magnificent instrument to tackle the mystery of the nebula. The new Hooker telescope allowed him to see individual stars in some nebulae, which no one had been able to do before. Hubble was able to measure the distance to the nebulae by identifying some of those stars as Cepheid variables, which, as we have explained, astronomers use as a standard candle.



Edwin Hubble (1889–1953) at the 100-inch Hooker telescope of California's Mount Wilson Observatory.

It turned out that the Cepheid variable stars were extremely faint, so the distance to the nearest one, located in the Andromeda nebula, was some 2 million light years, far outside the bounds of the Milky Way. Thus, with a single observation, Hubble established one of the most important facts about the universe we live in: it is made up of billions of galaxies, of which the Milky Way is but one.

We now know that each of these countless **galaxies** is an immense collection of millions to hundreds of billions of stars, together with gas, dust, and other materials, that is held together by the forces of mutual gravitational attraction. In making these discoveries, Hubble set the tone for a century of progress in the new branch of science called **cosmology,** which is devoted to the study of the structure and history of the entire universe.

The Milky Way is a rather typical galaxy. As shown in Figure 29-1, it is a flattened disk about 100,000 light-years across. A central bulge known as the nucleus holds most of our galaxy's hundreds of billions of stars. Bright regions in the disk, known as spiral arms, mark areas where new stars are being formed. About 75% of the brighter galaxies in the sky are of this spiral type (Figure 29-2).

Galaxies such as the Milky Way can be thought of as quiet, homey places, where the process of star formation and death goes on in a stately, orderly way. But a small number of galaxies—perhaps 10,000 among the billions known—are quite different, containing unusual objects, and are referred to collectively as "active" galaxies. The most spectacular of these unusual objects are the *quasars* (for quasi-stellar radio sources). Quasars are wild, explosive, violent objects, where as yet unknown processes pour vast

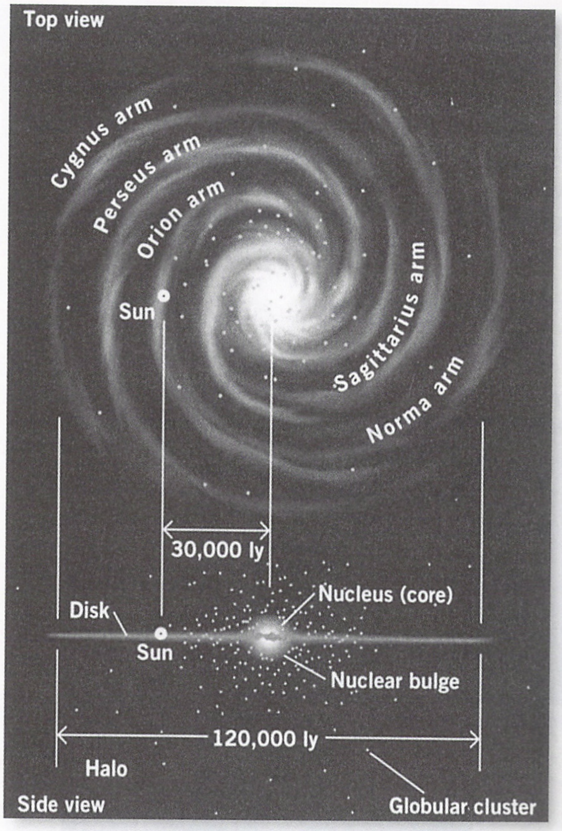


FIGURE 29-1. A map of the Milky Way galaxy, showing the nucleus and spiral arms.

FIGURE 29-2. The Whirlpool galaxy is a typical spiral galaxy, with a bright core and spiral arms where new stars are forming.

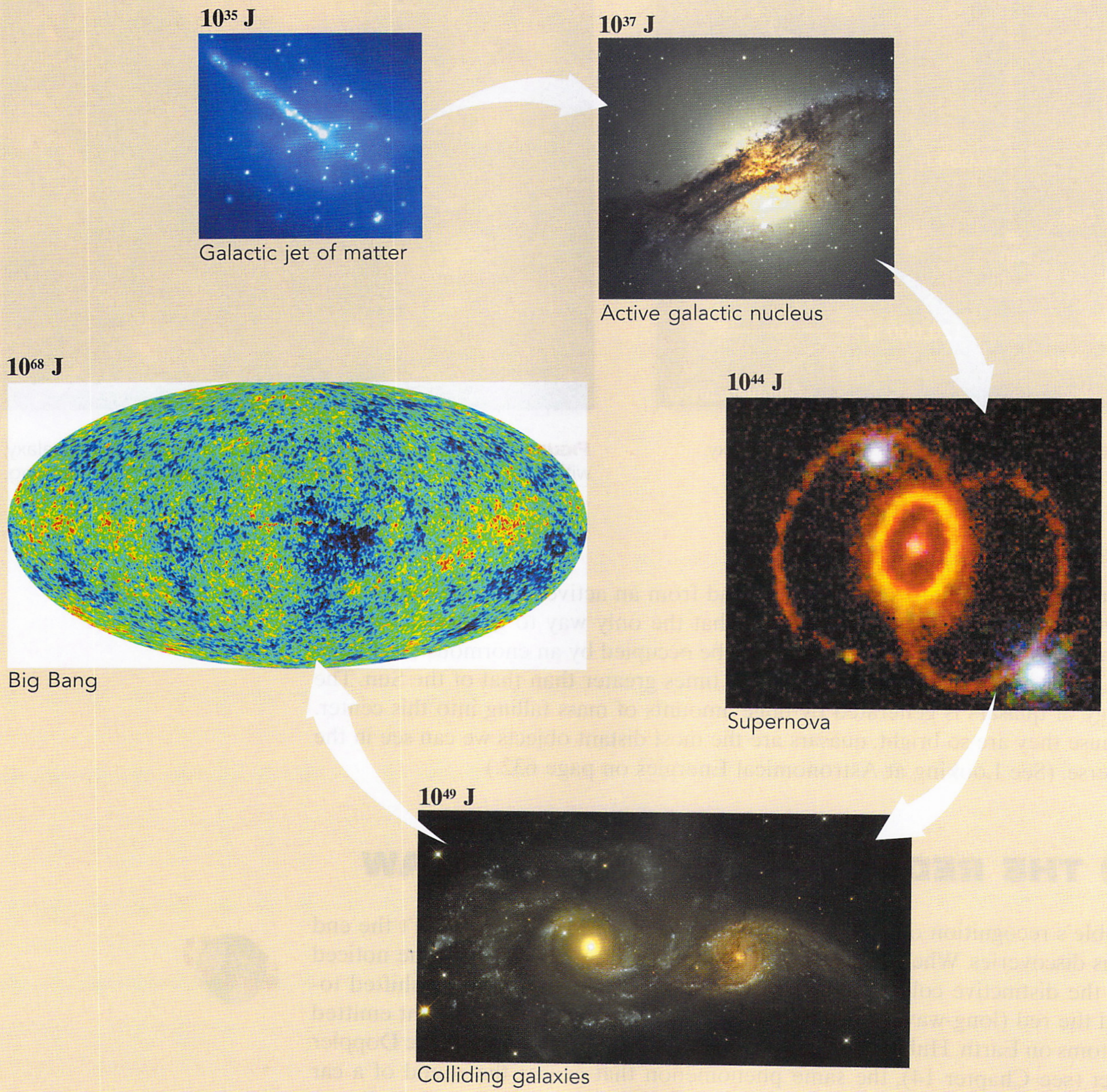
amounts of energy into space each second from an active center no larger than our solar system. Astronomers suggest that the only way to generate this kind of energy is for the center of a quasar to be occupied by an enormous black hole (see Chapter 28), with a mass millions of times greater than that of the Sun. The energy of quasars is generated by huge amounts of mass falling into this center. Because they are so bright, quasars are the most distant objects we can see in the universe. (See Looking at Astronomical Energies on page 632.)

THE REDSHIFT AND HUBBLE'S LAW

Hubble's recognition of galaxies other than our own Milky Way wasn't the end of his discoveries. When he looked at the light from nearby galaxies, he noticed that the distinctive colors emitted by different elements seem to be shifted toward the red (long-wavelength) end of the spectrum, compared to light emitted by atoms on Earth. Hubble interpreted this **redshift** as an example of the Doppler effect (see Chapter 14), the same phenomenon that causes the sound of a car whizzing past to change its pitch. Hubble's observation meant that distant

Looking at Astronomical Energies

There is nothing in human experience to compare with some of the events astronomers see in deep space. An exploding star (supernova) can radiate more energy than the Sun has emitted in its entire 5-billion-year lifetime. The centers of active galaxies outshine entire normal galaxies, with their billions of stars. Quasars are some of the most energetic objects known and are thought to result from black holes colliding when two galaxies come together. But the ultimate energy is the Big Bang itself, the beginning of our universe.



galaxies are moving away from Earth. Furthermore, Hubble noticed that the more distant a galaxy, the faster it is moving away from us (Figure 29-3).

On the basis of measurements of a few dozen nearby galaxies, Hubble suggested that a simple relationship exists between the distance of an object from Earth and that object's speed away from Earth. The farther away a galaxy is, the

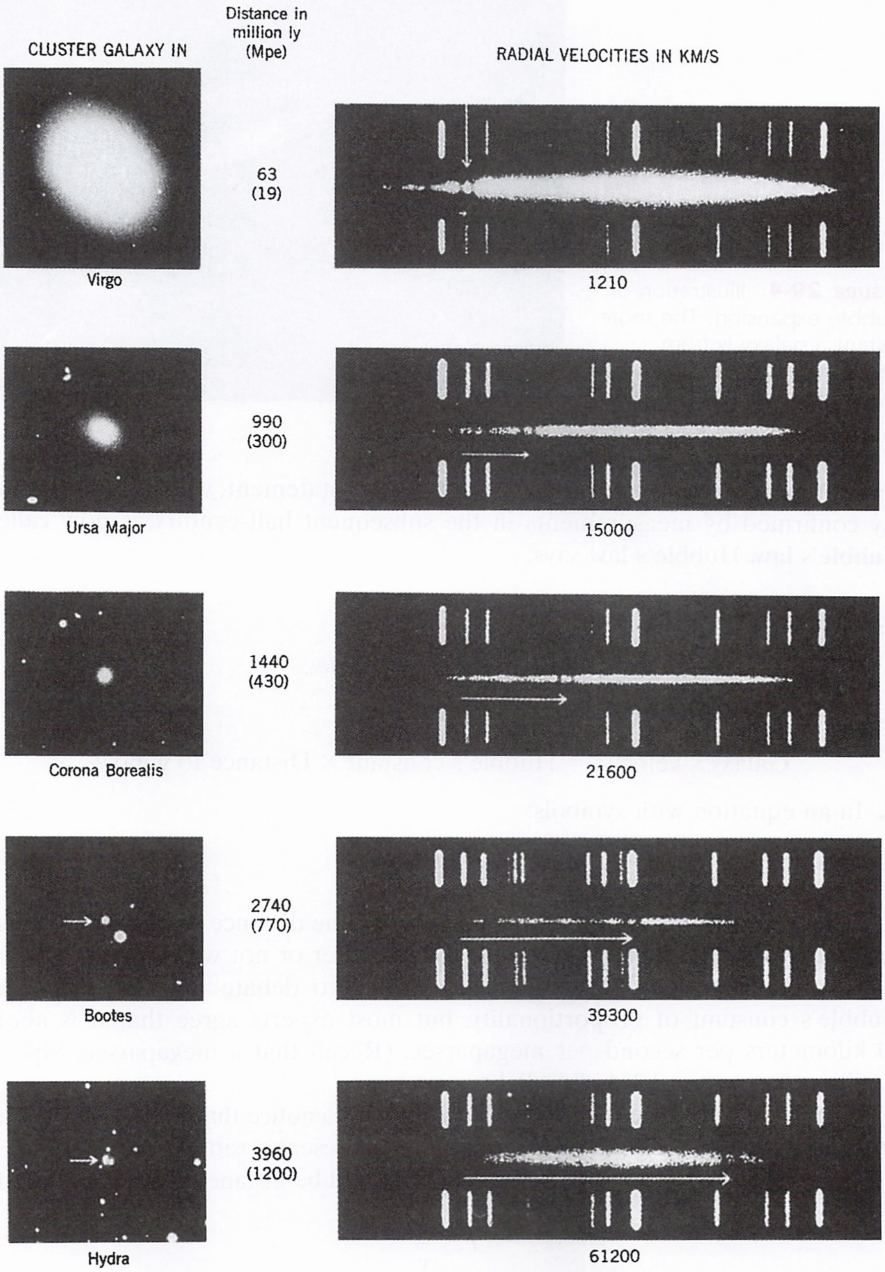


FIGURE 29-3. Photographs of galaxies as seen through a telescope (*left*), with spectra of those galaxies (*right*). The distance to each galaxy in megaparsecs is also given. Double dark lines in the spectra, characteristic of the calcium atom, are shifted farther to the right (toward the red) the farther away the galaxy is. Thus more-distant galaxies are traveling away from us at higher velocities. This phenomenon was used by Edwin Hubble to derive his law.

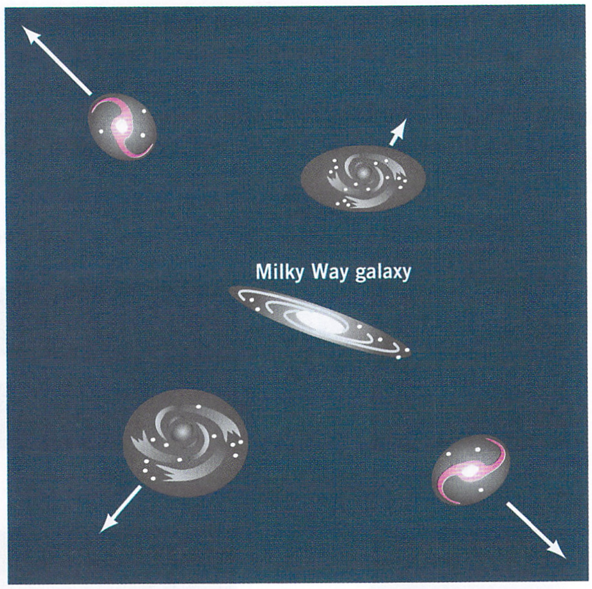


FIGURE 29-4. Illustration of Hubble expansion. The more distant a galaxy is from Earth, the faster it moves away from us.

faster it moves away from us (Figure 29-4). This statement, which has been amply confirmed by measurements in the subsequent half-century, is now called **Hubble's law.** Hubble's law says:

1. In words:

The farther away a galaxy is, the faster it recedes.

2. In an equation with words:

Galaxy's velocity = Hubble's constant × Distance to galaxy

3. In an equation with symbols:

$$v = H \times d$$

Hubble's law tells us that we can determine the distance to galaxies by measuring the redshift of the light we receive, whether or not we can make out individual stars in them. Astronomers continue to debate the exact value of Hubble's constant of proportionality, but most experts agree that it is about 70 kilometers per second per megaparsec. (Recall that a megaparsec, Mpc, is 1 million parsecs, or 3.3 million light-years.)

One way of interpreting Hubble's constant is to notice that if a galaxy were to travel from the location of the Milky Way to its present position with a velocity v, then the time it would take to make the trip would be distance divided by speed:

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

Substituting for v from Hubble's law,

$$t = \frac{d}{H \times d}$$

$$= \frac{1}{H}$$

Thus the Hubble constant provides a rough estimate of the time that the expansion has been going on and, hence, of the age of the universe. The current best estimate of the age of the universe is 13.7 billion years.

Connection

Analyzing Hubble's Data

In his original sample, Hubble observed 46 galaxies, but was able to determine distances to only 24. Some of his data are given in Table 29-1.

TABLE 29-1 Some of Hubble's Data

Distance to Galaxy (megaparsecs)	Velocity (km/s)
1.0	620
1.4	500
1.7	960
2.0	850
2.0	1090

How does one go about analyzing data such as these? One common way is to make a graph. In this case (Figure 29-5), the vertical axis is the velocity of recession of the galaxy and the horizontal axis is the distance to the galaxy. Figure 29-5*a* shows the data as originally plotted by Hubble, while Figure 29-5*b* presents a more recent compilation of many galaxies.

Looking at the original data, we see that the general trend of Hubble's law is obvious—the farther you go to the right (i.e., the farther away the galaxies are), the higher the points (i.e., the faster the galaxies are moving away). You also notice, however, that the points do not fall on a straight line but are scattered. Confronted with this sort of situation, you can do one of two things. You can assume that the scattering is due to experimental error and that more accurate experiments will verify that the points fall on a straight line; or you can assume that the scatter is a real phenomenon and try to explain it. Hubble took the first alternative, so the only problem left was to find the line about which experimental error was scattering his data.

The way this step is usually done is to find the line that comes closest to all the data points. The slope of this line, which measures how fast the velocity increases for a given change in distance, is the best estimate of Hubble's constant. ●

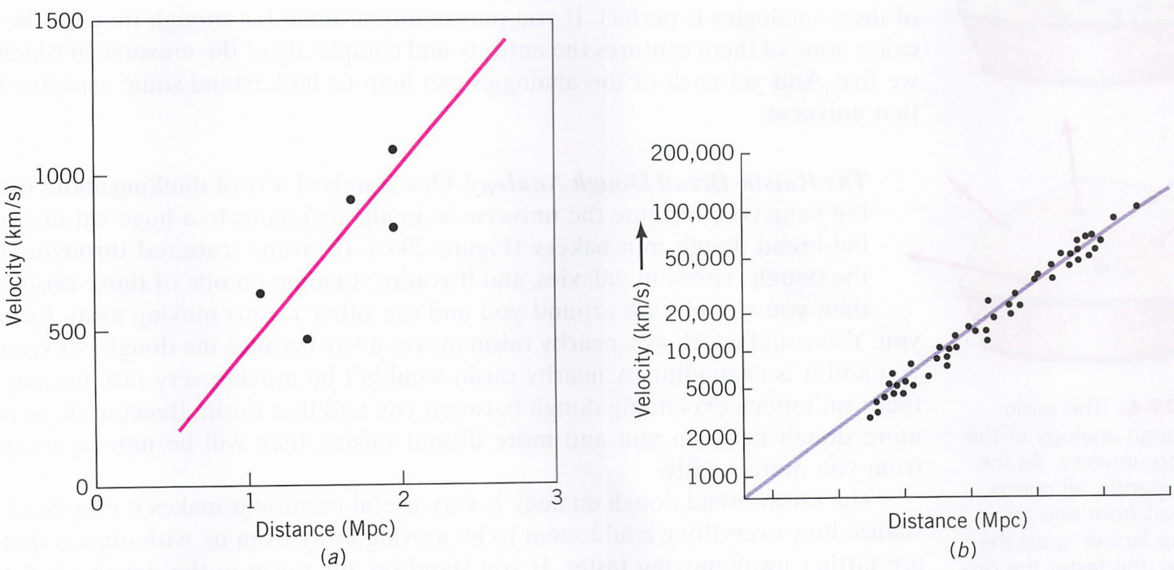


FIGURE 29-5. (*a*) Hubble's original distance-versus-velocity relationship. (*b*) A modern version, using many more galaxies.

THE BIG BANG

Hubble's law reveals an extraordinary aspect of our universe: it is expanding. Nearby galaxies are moving away from us and faraway galaxies are moving away even faster. The whole thing is blowing up like a balloon. This startling fact leads us, in turn, to perhaps the most amazing discovery of all. If you look at our universe expanding today and imagine moving backward in time (think of running a videotape in reverse), you can see that at some point in the past the universe must have started out as a very small object. In other words:

The universe began at a specific time in the past and has been expanding ever since.

This picture of the universe—that it began from a small, dense collection of matter and has been expanding ever since—is called the **big bang theory.** This theory constitutes our best idea of what the early universe was like.

Think how different the big bang theory of the universe is from the theories of the Greeks or the medieval scholars or even the great scientists of the nineteenth century whose work we have studied. To them, Earth went in stately orbit around the Sun, and the Sun moved among the stars, but the collection of stars you can see at night with your naked eye or with a telescope was all that there was. Suddenly, with Hubble's work, the universe grew immeasurably. Our own collection of stars, our own galaxy, is just one of perhaps 100 billion known galaxies in a universe in which galaxies are flying away from one another at incredible speeds. It is a vision of a universe that began at some time in the distant past and will, presumably, end at some time in the future.

Some Useful Analogies

The big bang picture of the universe is so important that we should spend some time thinking about it. Many analogies can be used to help us picture what the expanding universe is like, and we'll look at two. Be forewarned, however: none of these analogies is perfect. If you pursue any of them far enough they fail, because none of them captures the entirety and complexity of the universe in which we live. And yet each of the analogies can help us understand some aspects of that universe.

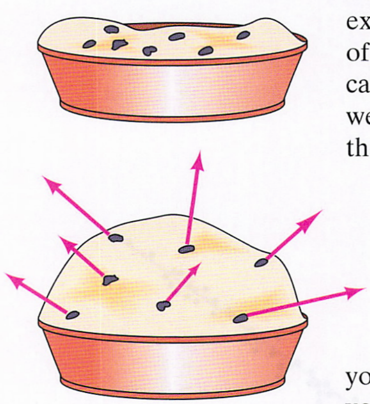


FIGURE 29-6. The raisin-bread dough analogy of the expanding universe. As the dough expands, all raisins move apart from one another. The farther apart the raisins are, the faster the distance increases.

The Raisin-Bread Dough Analogy One standard way of thinking about the big bang is to imagine the universe as being analogous to a huge vat of rising bread dough in a bakery (Figure 29-6). If raisins scattered throughout the dough represent galaxies, and if you're standing on one of those raisins, then you would look around you and see other raisins moving away from you. You could watch as a nearby raisin moves away because the dough between you and it is expanding. A nearby raisin wouldn't be moving very fast, because there isn't much expanding dough between you and that raisin. Because there is more dough between you and more distant raisins, they will be moving away from you more swiftly.

The raisin-bread dough analogy is very useful because it makes it easy to visualize how everything could seem to be moving away from us, with objects that are farther away moving faster. If you stand on any raisin in the dough, all the other raisins look as though they're moving away from you. This analogy thus

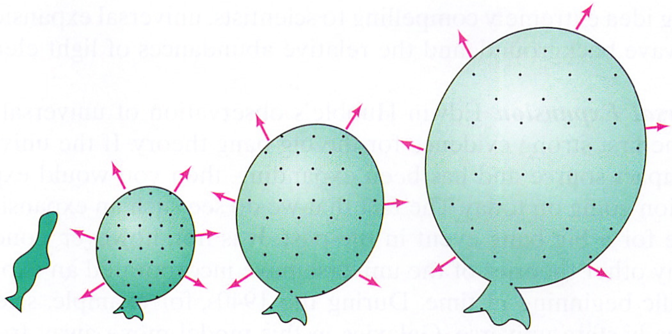


Figure 29-7. The expanding-balloon analogy of the universe. All points on the surface of the expanding balloon move away from one other. The farther apart the points, the faster they move apart.

explains why Earth seems to be the center of the universe. It also explains why this fact isn't significant—*every* point appears to be at the center of the universe.

But the expanding dough analogy fails to address one of the most commonly asked questions about the Hubble expansion: what is outside the expansion? A mass of bread dough, after all, has a middle and an outer surface; some raisins are nearer the center than others. But we believe that the universe has no surface, no outside and inside, and no unique central position. In this regard, the surface of an expanding balloon provides a better analogy.

The Expanding-Balloon Analogy Imagine that you live on the surface of a balloon in a two-dimensional universe. You would be absolutely flat, living on a flat-surface universe (similar to the way we are three-dimensional, living in a three-dimensional universe). Evenly spaced points cover the balloon's surface, and one of these points is your home. As the inflating balloon expands, you observe that every other point moves away from you—the farther away the point, the faster away it moves (Figure 29-7).

Where is the edge of the balloon? What are the inside and outside of the balloon in two dimensions? The answers, at least from the perspective of a two-dimensional being on the balloon's surface, are that every point appears to be at the center, and the universe has no edges, no inside, and no outside. The two-dimensional being experiences one continuous, never-ending surface. We live in a universe of higher dimensionality, but the principle is the same: our universe has no center and no inside versus outside.

The balloon analogy is also useful because it can help us visualize another question that is often asked about the expanding universe: what is it expanding *into*? If you think about being on the balloon, you realize that you could start out in any direction and keep traveling. You might come back to where you started, but you would never come to an end. There would never be an "into." The surface of a balloon is an example of a system that is bounded, but that has no "outside" (as seen in two dimensions). Similarly, the universe includes all space and is not expanding into anything.

Evidence for the Big Bang

In Chapter 1 we pointed out that every scientific theory must be tested and have experimental or observational evidence backing it up. The big bang theory provides a comprehensive picture of what our universe might be like, but are there sufficient observational data to support it? In fact, three pieces of evidence make the big bang idea extremely compelling to scientists: universal expansion, the cosmic microwave background, and the relative abundances of light elements.

The Universal Expansion Edwin Hubble's observation of universal expansion provided the first strong evidence for the big bang theory. If the universe began from a compact source and has been expanding, then you would expect to see the expansion going on today. The fact that we do see such an expansion is taken as evidence for a big bang event in the past. It is not, however, conclusive evidence. Many other theories of the universe have incorporated an expansion, but not a specific beginning in time. During the 1940s, for example, scientists proposed a steady-state universe. Galaxies in this model move away from one another, but new galaxies are constantly being formed in the spaces that are being vacated. Thus the steady-state model describes a universe that is constantly expanding and forming new galaxies, but with no trace of a beginning.

Because of the possibility of this kind of theory, the universal expansion, in and of itself, does not compel us to accept the big bang theory.

The Cosmic Microwave Background In 1964, Arno Penzias and Robert W. Wilson, two scientists working at Bell Laboratories in New Jersey, used a primitive radio receiver to scan the skies for radio signals. Their motivation was simple. They worked during the early days of satellite broadcasting, and they were measuring microwave radiation to document the kinds of background signals that might interfere with radio transmission. They found that whichever way they pointed their receiver, they heard a faint hiss in their apparatus. There seemed to be microwave radiation falling on Earth from all directions. We now call this radiation the **cosmic microwave background radiation.**

At first, Penzias and Wilson suspected that this background noise might be a fault in their electronics or even interference caused by droppings from a pair of pigeons that had nested inside their funnel-shaped microwave antenna. However, a thorough testing and cleaning made no difference in the odd results. A constant influx of microwave radiation of wavelength 7.35 centimeters flooded Earth from every direction in space. And so the scientists asked where is this radiation coming from?

In order to understand the answer to their question, you need to remember that every object in the universe that is above the temperature of absolute zero emits some sort of radiation (see Chapter 11). As we saw in the Physics Around Us section that opens this chapter, a coal in a fire may glow white-hot and emit the complete spectrum of visible electromagnetic radiation. As the fire cools, it gives out light that is first concentrated in the yellow, then orange, and eventually dull red range. Even after it no longer glows with visible light, you can tell that the coal is giving off radiation by holding out your hand to it and sensing the infrared or heat radiation that still pours from the dying embers. As the coal cools still more, it gives off wavelengths of longer and longer radiation.

One way to think about the cosmic microwave background, then, is to imagine that you are inside a cooling coal on a fire. No matter which way you look, you'll see radiation coming toward you, and that radiation shifts from white to orange to red light and, eventually, all the way down to microwaves as the coal cools.

In 1964, a group of theorists at Princeton University (not far from Bell Laboratories) pointed out that if the universe had indeed begun at some time in the past, then today it would still be giving off electromagnetic radiation in the microwave range. In fact, the best calculations at the time indicated that the radiation would be characteristic of an object at a few degrees above absolute zero. When Penzias and Wilson got in contact with these theorists, the reason they couldn't get rid of the microwave signal became obvious. Not only was it a real signal, it was evidence for the big bang itself. For their discovery, Penzias and Wilson shared the Nobel Prize in physics in 1978—not a bad outcome for a measurement designed to do something else entirely!

We have said before that it is possible to imagine theories, such as the steady-state theory, in which the universe is expanding but has no beginning. However, it is impossible to imagine a universe that does not have a beginning but that produces the kind of microwave background we're talking about. Thus Penzias and Wilson's discovery put an end to the steady-state theory.

In 1989, the Cosmic Background Explorer satellite measured the microwave background to extreme levels of accuracy. The purpose of this measurement was to see, in great detail, whether the predictions of the big bang theory about the nature of the cosmic microwave background radiation were correct. These data established beyond any doubt that we live in a universe where the average temperature is 2.7 kelvins. This finding reaffirmed the validity of the big bang theory in the minds of scientists.

In 2003, new data from a satellite called the Wilkinson Microwave Anisotropy Probe (WMAP) was released. Launched in June of 2001, this satellite has been collecting data of unprecedented accuracy by making extremely detailed measurements of small differences in the microwaves reaching Earth from different directions in space. Many of the detailed results about the age and composition of the universe used in this chapter come from an analysis of the WMAP data.

The Abundance of Light Elements The third important piece of evidence for the big bang theory comes from studies of the abundances of light nuclei in the universe. For a short period in the early history of the universe, as we see at the end of this chapter, atomic nuclei could form from elementary particles. Cosmologists believe that the only nuclei that could have formed in the big bang are isotopes of hydrogen, helium, and lithium (the first three elements, with one, two, and three protons in their nuclei, respectively). All elements heavier than lithium were formed later in stars.

The conditions necessary for the formation of light elements were twofold. First, matter had to be packed together densely enough to allow collisions that would produce a fusion reaction (see Chapter 26). Second, the temperature had to be high enough for those reactions to happen, but not so high that nuclei created by fusion would be broken up in subsequent collisions. In an expanding universe, the density of matter decreases rapidly because of the expansion, and each type of nucleus can form only in a very narrow range of conditions. Calculations based on density and collision frequency, together with known nuclear reaction rates, make rather specific predictions about how much of each isotope could have been made before matter spread too thinly. Thus the cosmic abundances of elements such as deuterium (the hydrogen isotope with one proton and one neutron in its nucleus), helium-3 (the helium isotope with two protons and one neutron), and helium-4 (with two protons and two neutrons) comprise another test of our theories about the origins of the universe.

In fact, studies of the abundances of these isotopes find that they agree quite well with the predictions made in this way. The prediction for the primordial abundance of helium-4 in the universe, for example, is that it cannot have exceeded 25% of all atoms. Observations of helium abundance are quite close to this prediction. If the abundance of helium differed by more than a few percent from this value, the theory would be in serious trouble.

THE EVOLUTION OF THE UNIVERSE

Our vision of an expanding universe leads us to peer back in time, to the early history of matter and energy. What can we say about the changes that must have taken place during the past 15 billion years?

Some General Characteristics of an Expanding Universe

Have you ever pumped up a bicycle tire with a hand pump? If you have, you may have noticed that after you've run the pump for a while, the barrel gets very hot. All matter heats up when it is compressed.

The universe is no exception to this rule. A universe that is more compressed and denser than the one in which we live would also be hotter on average. In such a universe, the cosmic background radiation would correspond to a temperature much higher than 2.7 K (which is what it is today), and the wavelength of the background radiation would be shorter than 7.35 cm.

When the universe was younger, it must have been much hotter and denser than it is today. This cardinal principle guides our understanding of how the universe evolved. In fact, the big bang theory we have been discussing is often called the "hot big bang" to emphasize the fact that the universe began in a very hot, dense state and has been expanding and cooling ever since.

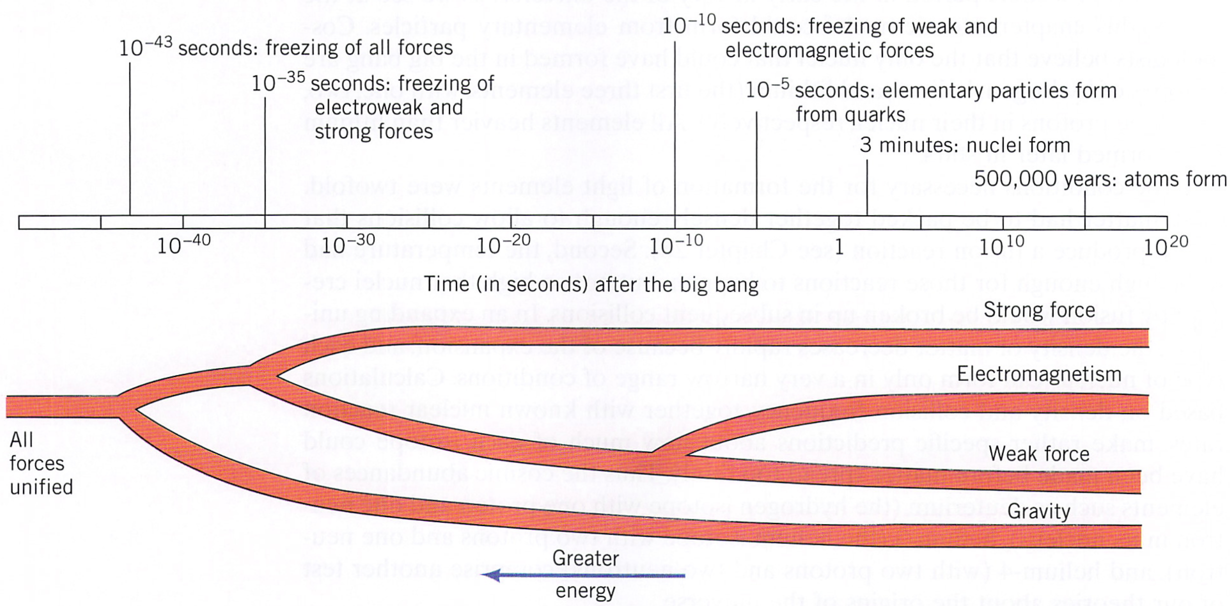


FIGURE 29-8. The sequence of "freezings" in the universe since the big bang. The earliest freezings involve the splitting of forces, while later freezings involve forms of matter.

In Chapter 9 we saw that changes of temperature may correspond to changes of state in matter. For example, if you cool water it eventually turns into ice at the freezing point. In just the same way, modern theories claim, as the universe cooled from its hot origins, it went through changes of state very much like the freezing of water. We refer to these dramatic changes in the fabric of the universe in technical language as "phase transitions," or, more colloquially, as *freezings,* even though they are not actually changes from a liquid to a solid state.

A succession of freezings dominates the history of the universe. Six distinct episodes occurred, and each had its own unique effect on the universe that we live in. Between each pair of freezings was a relatively long period of steady and rather uneventful expansion. Once we understand these crucial transitions in the history of the universe, we will have come a long way toward understanding why the universe is the way it is.

Let's look at the transitions in order, from the earliest to the most recent, as summarized in Figure 29-8. The first set of freezings involves the unification of forces we discussed in Chapter 27, and the last set involves the coming together of particles to form more complex structures, such as nuclei and atoms.

10^{-43} Second: The Freezing of All Forces

Cosmologists calculate that the first freezing after the beginning of the universe took place at about 10^{-43} second. (This is a really small number: 0.0000000000000000000000000000000000000000001 second!) Before this time, there was only a single unified force. At 10^{-43} second, the gravitational force split off from the strong–electroweak force, so there were two fundamental forces acting in nature.

We can't reproduce in our laboratories the unimaginably high temperatures that existed at this freezing, and we do not have successful theories that describe the unification of gravity with the other forces. Thus, this earliest freezing remains both the theoretical frontier and the limit of our knowledge about the universe at the present time.

10^{-35} Second: The Freezing of the Electroweak and Strong Forces

Unified field theories that describe the behavior of all matter and forces (see Chapter 27) tell us that before the universe was 10^{-35} second old, the strong force was unified with the electroweak force. At 10^{-35} second, the strong force split off from the electroweak force. That is, before this time there were only two fundamental forces acting in the universe (the strong–electroweak force and the gravitational force), but after this time there were three.

Two important events are associated with the freezing at 10^{-35} seconds: the elimination of antimatter and inflation.

The Elimination of Antimatter Antimatter (see Chapter 27) is fairly rare in the universe we live in. It wasn't until the twentieth century that scientists were able to identify antimatter, and we presently have compelling evidence that no large collections of antimatter exist anywhere in the universe. For example, spaceships have landed on the Moon, Mars, and Venus, and if any of those bodies had been made of antimatter, those spaceships would have been annihilated in a massive burst of gamma rays. Because they were not, we conclude that none of those planets is made of antimatter.

By the same token, the solar wind, composed of ordinary matter, is constantly streaming outward from the Sun to the farthest reaches of the solar system. If any objects in the solar system were made of antimatter, the protons in the solar wind would be annihilating with materials in that body and we would see evidence of it. The entire solar system, therefore, is made of ordinary matter. By the same type of argument, scientists have been able to show that our entire galaxy is made of ordinary matter and that no clusters of galaxies anywhere in the observable universe are made of antimatter.

The question, then, is this: if antimatter is indeed simply a mirror image of ordinary matter and if antimatter appears in our theories on an equal footing with ordinary matter, as it does, then why is there so little antimatter in the universe?

Unified field theories give us an explanation of this striking feature of the cosmos. In experiments, we find one instance of a particle that decays preferentially into matter over antimatter—a particle whose decay products more often contain more matter than antimatter. This particle is called the K^0_L ("K-zero-long"), one of the many heavy particles (such as protons and neutrons) that were discovered in the second half of the twentieth century.

If you take the theories that are successful in explaining this laboratory phenomenon and extrapolate them to the very early universe, you find that there were about 100,000,001 protons made for every 100,000,000 antiprotons. In the maelstrom that followed the big bang, the 100,000,000 antiprotons annihilated with 100,000,000 protons, leaving only a sea of intense radiation to mark their presence. From the collection of leftover protons, all the matter in the universe (including Earth and its environs) was made. This discovery allowed physicists to explain the puzzling absence of antimatter in the universe, and in the 1980s led to a burst of interest in the evolution of the early universe.

Inflation According to the most widely accepted versions of the unified field theories, the freezing at 10^{-35} second was accompanied by an incredibly rapid (but short-lived) increase in the rate of expansion of the universe. This short period of rapid expansion is called *inflation,* and theories that incorporate this phenomenon are called "inflationary theories."

One way to think about inflation is to remember that changes in volume are often associated with changes of state. Water, for example, expands when it freezes, which explains why water pipes may burst open when the water in them freezes in very cold weather. In the same way, scientists argue, the universe underwent a period of very rapid expansion during the time when the strong force froze out from the electroweak. Roughly speaking, at this time the universe went from being much smaller than a single proton to being about the size of a grapefruit, an incredible increase in size of about 10^{50} times (Figure 29-9).

Inflation explains another puzzling feature of the universe. We have repeatedly observed that the cosmic microwave background (which is an index of the temperature of the universe) is remarkably uniform. The temperatures associated with microwaves coming from one region of the sky differ from those coming from another region by no more than 1 part in 1000. But calculations based on a uniform rate of expansion say that different parts of the universe would not have been close enough together to establish a common temperature.

In the inflationary theory, the resolution of this problem is simple. Before 10^{-35} second, all parts of the universe were in contact with one another because the universe was much smaller than you would have guessed based on a uniform

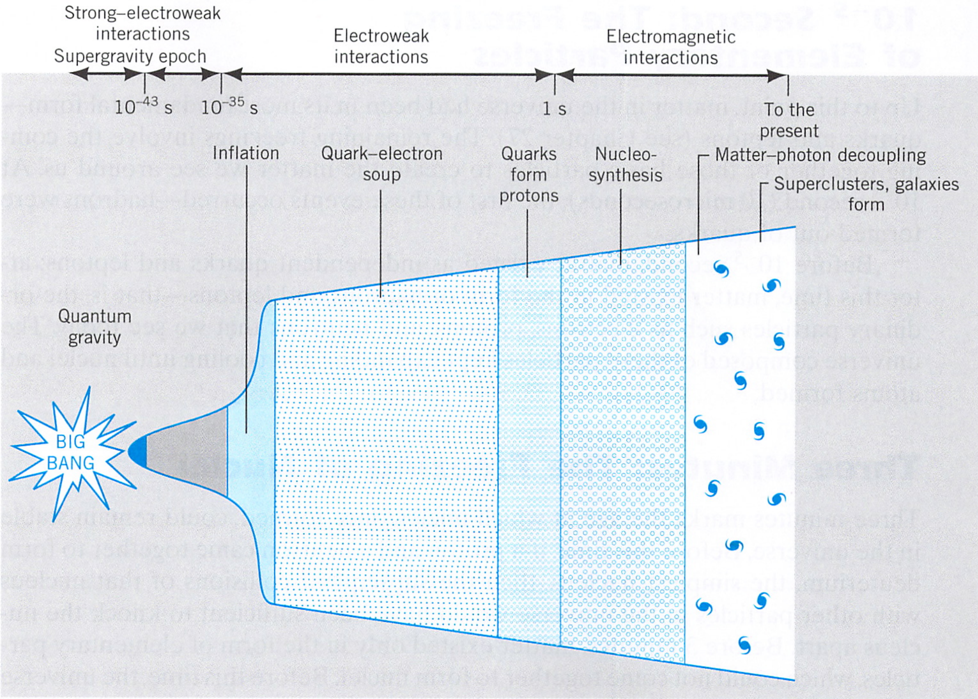


FIGURE 29-9. The evolution of the universe through the succession of freezings. Note the rapid expansion associated with the inflationary period.

rate of expansion. There was time to establish equilibrium before inflation took over and increased the size of the universe. The temperature equilibrium, established early, was preserved through the inflationary era and is seen today in the uniformity of the microwave background.

Thus the coming together of the theories of elementary particle physics and the study of cosmology has produced solutions to long-standing problems and questions about the universe.

10^{-10} Second: The Freezing of the Weak and Electromagnetic Forces

Before 10^{-10} second (that's 1 ten-billionth of a second), the weak and the electromagnetic forces were unified. In other words, before 10^{-10} second, there were only three fundamental forces operating in the universe. These were the strong, gravitational, and electroweak forces. After 10^{-10} second, the full complement of four fundamental forces was present.

The time of 10^{-10} second also marks another milestone in our discussion of the evolution of the universe. The modern particle accelerators of high-energy physics can just barely reproduce the incredible concentration of energy associated with that event. This means that from this point forward it is possible to have direct experimental checks of the theories that describe the evolution of the universe.

10^{-5} Second: The Freezing of Elementary Particles

Up to this point, matter in the universe had been in its most fundamental form—quarks and leptons (see Chapter 27). The remaining freezings involve the coming together of those basic particles to create the matter we see around us. At 10^{-5} second (10 microseconds), the first of these events occurred—hadrons were formed out of quarks.

Before 10^{-5} second, matter existed as independent quarks and leptons; after this time, matter existed in the form of hadrons and leptons—that is, the ordinary particles such as electrons, protons, and neutrons that we see today. The universe composed of these particles kept expanding and cooling until nuclei and atoms formed.

Three Minutes: The Freezing of Nuclei

Three minutes marks the age at which nuclei, once formed, could remain stable in the universe. Before this time, if a proton and a neutron came together to form deuterium, the simplest nucleus, then the subsequent collisions of that nucleus with other particles in the universe would have been sufficient to knock the nucleus apart. Before 3 minutes, matter existed only in the form of elementary particles, which could not come together to form nuclei. Before this time, the universe consisted of a sea of high-energy radiation whizzing around between all the various species of elementary particles we discussed in Chapter 27.

At 3 minutes, a short burst of nucleus formation occurred, as we have discussed earlier. Thus from 3 minutes on, the universe was littered with nuclei, which formed part of the plasma, the hot fluid mixture of electrons and simple nuclei that was the material of the early universe. Remember, however, that only nuclei of the light elements—hydrogen, helium, and lithium—were made at this time.

Before One Million Years: The Freezing of Atoms

The most recent transition occurred gradually between the time that the universe was a few hundred thousand and 1 million years old. At this time, the background temperature of the hot, dense universe was so great that electrons could not settle within atomic orbits to form atoms. Even if an atom formed by chance, its subsequent collisions were sufficiently violent that the atom could not stay together. Thus all of the universe's matter was in the form of plasma.

This freezing of atoms marks an extremely important point in the history of the universe because it is a point at which radiation such as light was no longer locked into the material of the universe. You know from experience that light can travel long distances through the atmosphere (which is made of atoms). But light cannot travel freely through plasma, which quickly absorbs light and other forms of radiation. Thus when atoms formed, the universe became transparent and radiation was released. It is this radiation, cooled and stretched out, that we now see as the cosmic microwave background. Thus, the cosmic microwave background is a picture of the universe at this time.

The formation of atoms marks an important milestone for another reason. Before this event, if clumps of matter happened to begin forming (under the influence of gravity, for example), they would absorb radiation and be blown apart. This means that there must have been a window of opportunity for the formation of galaxies. If galaxies are made of ordinary matter, they couldn't have started to come together out of the primordial gas cloud until atoms had formed, about 500,000 years after the big bang. By that time, however, the Hubble expansion had spread matter out so thinly that the ordinary workings of the force of gravity would not have been able to make a universe of galaxies, clusters, and superclusters. Known as the "galaxy problem," this puzzle remains the great riddle that must be answered by cosmologists.

Another way of stating this problem is to compare the clumpiness of matter in the universe to the smoothness of the cosmic background radiation. The background radiation seems to be pretty much the same no matter which way you look in the universe. This uniformity argues that the universe had a smooth, regular beginning. How can this statement be reconciled with the lumpy structure we see when we look at the distribution of matter?

DARK MATTER

As complete as this history of the early universe may seem, significant gaps in our understanding of the evolution of the universe remain. Some of these gaps were closed with the development of unified field theories and the inflationary scheme of the universe. However, the problem of explaining the existence of galaxies, clusters, and superclusters remains.

It now appears that all the impressive luminous objects in the sky constitute less than 10% of the matter in the universe, perhaps a good deal less than 10%. The rest of the matter exists in forms that we cannot see, but whose effects we can measure. This mysterious new kind of material is called **dark matter.**

The easiest place to see evidence for dark matter is in galaxies such as our own Milky Way. Far out from the stars and spiral arms that we normally associate with galaxies, we can still see a diffuse cloud of hydrogen gas. This gas gives off radio waves, so we can detect its presence and its motion. In particular, we can tell how fast it is rotating. When we do these sorts of measurements, a rather startling fact emerges. In Chapter 3 we saw that Kepler's laws implied that any object orbiting around a central body under the influence of gravity will travel slower the farther out it is. The distant planet Jupiter, for example, moves more slowly in orbit around the Sun than does Earth. Similarly, you would expect that when hydrogen molecules are far enough away from the center of a galaxy, these more distant atoms would move more slowly than those closer in. Even though we can see these hydrogen atoms out to distances three times and more the distance from the center of the Milky Way to the end of the spiral arms, no one has ever seen the predicted slowing down.

The only way to explain this phenomenon is to say that those hydrogen atoms are still in the middle of the gravitational influence of the galaxy. This means that luminous matter—the bright stars and spiral arms—is not the only thing that is exerting a gravitational force. Something else, something that makes up at least 90% of the mass of the galaxy and that extends far beyond the stars, exerts a gravitational force and affects the motion of the hydrogen we observe. Studies of other galaxies show the same effect and scientists have found evidence that dark matter exists in the voids between galaxies as well. The most recent estimates tell us that about 4% of the matter in the universe is ordinary stuff such as that found in stars, and that about 23% is in the form of dark matter. The rest of the matter in the universe is in a newly discovered form called "dark energy," which we discuss in the next section.

Dark matter is strange, indeed. It does not interact through the electromagnetic force. If it did, it would absorb or emit photons and it wouldn't be "dark" in the sense we're using the term here. Yet because we know that it exerts a gravitational attraction, we can conclude that this unseen stuff must be a form of matter—matter that interacts with ordinary matter only through the gravitational force. Detecting dark matter, and finding out what it is, remains a very active research field today.

The existence of dark matter might help us understand a key event in the early history of the universe, because dark matter could have formed into clumps before atoms formed. In the first several hundred thousand years after the big bang, photons blew apart collections of luminous matter that were trying to form galaxies, but light would not have affected the clumping of dark matter. Therefore, when atoms formed and luminous matter could clump together, that matter found itself in a universe in which large clusterings of dark matter already existed. The luminous matter would simply have fallen into these clusters and would not have had to form under the influence of its own gravitational attraction. Thus, if dark matter exists and if dark matter formed clumps early in the history of the universe, the problem of structure is solved.

DARK ENERGY AND THE END OF THE UNIVERSE

When most people think about the Hubble expansion they wonder whether the universe will continue to expand forever or will someday fall back in on itself. In the case of eternal expansion, astronomers say that the universe is open; in the case of eventual collapse, they say that the universe is closed. Finally, in the intermediate case between the two, in which universal expansion slows down, but never quite stops, the universe is said to be flat. Can we tell which kind of universe we live in?

The way that scientists have approached this question is to note that the force pulling back on distant galaxies is the gravitational attraction associated with the mass of the universe. If there is enough mass, the outward motion of the galaxy will be slowed down and reversed. If there isn't enough mass, the expansion will be slowed but never stopped. The luminous matter of the universe—stars, nebulae, and dust clouds—is only about 0.1% of the mass needed to close the universe. Even counting dark matter brings us only up to about 20% to 30% of the needed value. Just from counting mass, then, we would conclude that we live in an open universe.

In 1999, astronomers announced a surprising result that confirms this conclusion. Using a new standard candle called a Type Ia supernova, they have measured the distances to the most distant galaxies. Using the fact that light from those galaxies has been traveling toward us for billions of years, they can compare the rate of expansion of the universe as it was long ago to what it is today. The surprising result is that the expansion of the universe isn't slowing down at all—in fact, it's speeding up! This observation suggests that there may be a new kind of force acting over the vast distances between the galaxies. This force seems to behave like a kind of antigravity that pushes galaxies apart. Cosmologists call this new discovery **dark energy.** As is the case with dark matter, we don't yet know what it is, and because of its recent discovery dark energy is, at the moment, even more mysterious than dark matter. Whatever it is, however, the results from the WMAP program previously discussed indicate that it makes up approximately 73% of the mass of the universe. (Remember that mass and energy are related through Einstein's equation $E = mc^2$).

Although it may seem that cosmologists are piling mystery upon mystery with these new discoveries, in fact each new mystery gets us closer to an understanding of our universe. The process is a little like baking a cake—you have to know what all the ingredients are before you can succeed. With the discovery of dark energy, cosmologists believe that they have completed the list of ingredients and can get down to the job of figuring out how they all fit together.

THINKING MORE ABOUT

Cosmology: The History of the Universe

The story of the big bang that we have just recounted has one clear feature: there were no human beings around to observe any of the events we've just described. In 1999, creationists on the Kansas Board of Education used this fact as a reason to ban questions about the big bang from statewide high school scientific achievement tests. Let's think for a moment about the kind of evidence we require to establish the existence of events in the past.

How do you know there was an event called the American Civil War? No one alive today actually took part in the Civil War, yet no one suggests that we should doubt its existence. The reason is that there is all sorts of evidence in the form of texts, artifacts, documents, and even recorded stories told by survivors before they died. The weight of this evidence is so overwhelming that the existence of the war is universally accepted.

But what about events farther back in time—the Crusades, for example, or the Thirty Years War? The evidence here is weaker than that for the Civil War. What about events that occurred before the invention of writing—the arrival of the first humans in North America, for example? Here the evidence is exclusively in the form of archaeological data. And what about geological events where the evidence is in the rocks themselves?

The evidence for the big bang has been outlined in this chapter. How does it compare to the evidence for other events in the past? How much evidence is required to establish the existence of such events? Why do you suppose so few scientists agree with the decision of the Kansas school board? (By the way, this decision was reversed by a new school board elected in 2002.)

Summary

Early in the twentieth century, Edwin Hubble made two extraordinary discoveries about the structure and behavior of the universe, the science we call **cosmology.** First, he demonstrated that our home, the collection of stars known as the **Milky Way,** is just one of countless **galaxies** in the universe, each containing billions of stars. By measuring the **redshift** of galaxies, he also discovered that these distant objects are moving away from one another. According to **Hubble's law,** the farther the galaxy, the faster it is moving away. This relative motion implies that the universe is expanding.

One theory that accounts for universal expansion is the **big bang theory**—the idea that the universe began at a specific moment in time and has been expanding ever since. Evidence from the **cosmic microwave background radiation** and the relative abundances of light elements, in addition to expansion, support the big bang theory.

At the moment of creation, all forces and matter were unified in one unimaginably hot and dense volume. As the universe expanded, however, a series of six "freezings" led to the universe we see today. Freezings at 10^{-43} second, 10^{-35} second, and 10^{-10} second caused a single unified force to split progressively into the four forces we observe today: the gravitational, strong, electromagnetic, and weak forces. At that early stage of the universe, when all matter and energy were contained in a volume no larger than a grapefruit, matter was in its most elementary form of quarks and leptons.

At 10^{-5} second, the quarks bonded together to form heavy nuclear particles such as protons and neutrons. Subsequent freezings saw these particles first fuse into nuclei at 3 minutes and ultimately join with electrons to form atoms at 500,000 years. Stars, which formed from those atoms, then could begin the processes that provided all the other chemical elements.

Understanding **dark energy** that pushes galaxies apart and the search for **dark matter**—mass that we cannot see with our telescopes—is a research frontier that may help us determine whether or not the universe will continue expanding forever.

Key Terms

big bang theory The theory that the universe was, at one time, a very small, dense collection of matter and energy that has been expanding ever since. (p. 636)

cosmic microwave background radiation The electromagnetic radiation from space that is thought to be a remnant of the big bang. (p. 638)

cosmology The branch of science devoted to the study of the history and structure of the universe. (p. 630)

dark energy Newly discovered energy that has the effect of pushing galaxies apart. (p. 647)

dark matter The unseen matter in the universe that has been postulated to account for the observed structure of the universe. (p. 645)

galaxy a collection of gas, dust, and millions or billions of stars all held together by gravity; there are billions of galaxies in the universe. (p. 630)

Hubble's law The law that relates the distance between Earth and a galaxy to the galaxy's recession speed. (p. 634)

Milky Way The galaxy that is home to Earth and our solar system. (p. 627)

redshift The shift toward lower frequencies of the spectra of galaxies moving away from us. (p. 633)

Key Equation

Hubble's Law: Galaxy's velocity = Hubble's constant × Distance to galaxy

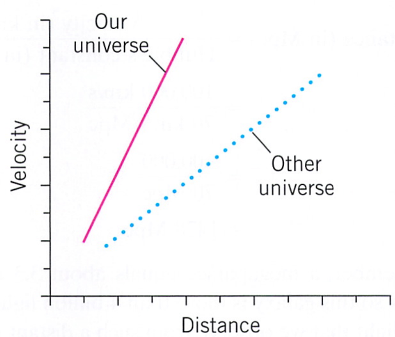
Review

1. What is cosmology? How does it differ from astronomy?
2. What is a standard candle? How can it be used to measure distances between stars?
3. Why are Cepheid variables frequently used as a standard candle?
4. What is a galaxy? How does a galaxy differ from a star?
5. What galaxy do we live in? How large is it?
6. How did Edwin Hubble discover that there are galaxies in the universe other than the Milky Way?
7. What does the term "quasar" stand for? What is thought to be at the center of these types of galaxies?
8. How does the light we see from distant stars become red-shifted? What does this redshift say about the universe?
9. Describe Hubble's law. How did Hubble discover it?
10. What is the best current estimate of the age of the universe? How was this estimated?
11. What is the big bang theory? Why is it sometimes called the "hot big bang"?
12. Two analogies were presented to explain the expansion of the universe. One presents the expanding universe as expanding dough filled with raisins, while the other is an analogy of the universe as an expanding balloon. What are the strengths and weaknesses of each of these analogies?
13. What kinds of evidence support the big bang theory?
14. How did the now-discarded steady-state theory explain the expansion of the universe?
15. Why was the steady-state theory of the universe abandoned? How does this episode fit into the discussion of the scientific method in Chapter 1?

16. What is the significance of the discovery by Penzias and Wilson of cosmic microwave background radiation?
17. What is the average temperature of the universe we live in? How do we know this?
18. If the universe were hotter than the temperature in Review Question 17, would the universe be older or younger? Similarly, what would the relative age be if the universe were colder than this?
19. Which elements do cosmologists think were formed in the big bang? How abundant are these elements today, and what does this imply?
20. Make a table with ages of the universe in the left column (10^{-43} seconds, 10^{-35} seconds, 10^{-10} seconds, 10^{-5} seconds, 3 minutes, 500,000 years) and the major events in the history of the universe in the right column.
21. Why is the universe composed of matter and not antimatter?
22. What is inflation? When did it occur, and what puzzling feature of the universe does it help explain?
23. What do we mean when we say that light was locked into the material of the universe before atoms formed? When was this light released?
24. What is the galaxy problem?
25. Dark matter probably makes up over 90% of the matter in the universe. What is it and what evidence is there that it exists?
26. How can dark matter help provide an explanation for the clumpiness of matter in the universe?
27. What will be the fate of the universe? Is the universe open, closed, or flat?
28. What measurements or observations contribute to the question of whether the universe is closed or open?
29. Some advances in our knowledge have been made possible through better equipment, such as Hubble's discoveries using the 100-inch Hooker telescope at Mount Wilson. What other major discoveries in cosmology have relied on improvements in existing apparatus?
30. Describe how the universe is moving at present. Is it accelerating or decelerating?
31. What is dark energy?

Questions

1. Why does Earth seem to be at the center of the Hubble expansion?
2. If the universe is closed, describe the results that some future Hubble will get when he looks through a telescope during the period of contraction. Will he still see other galaxies? Will he still see a redshift?
3. Suppose that scientists were able to travel to a different universe. The figure shows a distance-versus-velocity graph for galaxies measured in the two universes. The solid line represents the data for our universe; the dotted line is the data for the new universe. Which universe is older? Explain.



4. If a life form on a planet in a distant galaxy measured the Hubble constant from its location, would you expect that it would get the same value that we measure here from Earth? (We'll assume that we use the same units of measurement.) Why would a different Hubble constant cause scientists to question our current understanding of the universe?
5. Suppose that a new experiment showed that the wavelength of the cosmic background radiation were slightly shorter than its previously measured value. How would that change our estimate of the average temperature of the universe?
6. What is meant by the term "freezings" in the explanations of the current cosmological model? How can enormously high temperatures prevent the formation of particles such as nuclei or atoms?
7. If the universe were expanding more rapidly than it presently is, would the Hubble constant be affected? If so, how?
8. If all that you knew was the energy per square meter that the Sun radiated on the surface of Earth, could you determine the distance from the Sun to Earth?
9. We say that galaxies moving away from us are redshifted. What would we say about galaxies if they were all moving toward us?

Problem-Solving Examples

EXAMPLE 29-1 Measuring Distance with a Standard Candle

A 100-watt lightbulb shines in the center of a large darkened room. We have a light meter that measures 20 cm by 5 cm (0.01 m^2). The light meter detects a power of 0.007 watt falling on it when the light is on. What is the distance between the light and the meter?

REASONING AND SOLUTION: We solve this problem by assuming that the 100 watts of power that the lightbulb emits radiates equally in all directions (Figure 29-10). Imagine a sphere of radius R centered on the bulb and including the detector. (Note that R, the radius of the sphere, is also the unknown distance between the light and the light meter.) The total surface area of the sphere is:

$$\text{Area} = 4\pi R^2$$

The fraction of that surface covered by the detector is:

$$\text{Fraction of area} = \frac{\text{Area of detector}}{\text{Area of sphere}} = \frac{0.01\ \text{m}^2}{4\pi R^2}$$

Similarly, the fraction of the total light from the bulb that falls on the meter is:

$$\text{Fraction of light} = \frac{\text{Light falling on meter}}{\text{Total light emitted}} = \frac{0.007\ \text{watt}}{100\ \text{watts}} = 7.0 \times 10^{-5}$$

To find R, we note that these two fractions must be equal to one another (that is, the fraction of light falling on the meter must be the same as the fraction of the imaginary sphere that the meter covers), or

$$\text{Fraction of area} = \text{Fraction of light}$$

$$= \frac{0.01\ \text{m}^2}{4\pi R^2} = 7.0 \times 10^{-5}$$

So the distance we seek is

$$R = 3.37\ \text{m}$$ ●

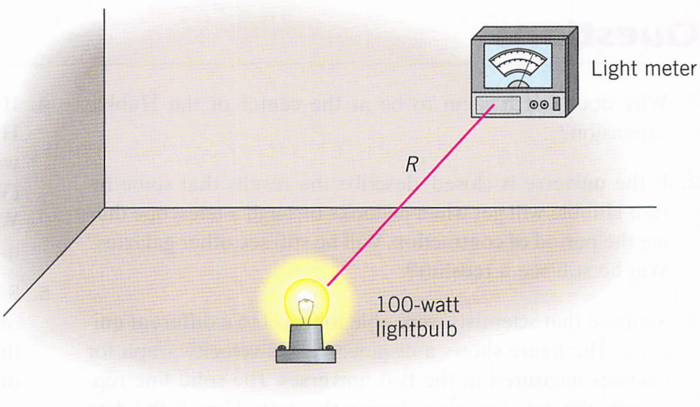


FIGURE 29-10. If you know how much light a standard candle emits, then you can determine its distance.

EXAMPLE 29-2 The Distance to a Receding Galaxy

Astronomers discover a new galaxy and determine from its redshift that it is moving away from us at approximately 100,000 km/s (about one-third the speed of light). Approximately how far away is this galaxy? Assume a value of 70 km/s/Mpc for the Hubble constant.

REASONING: According to Hubble's law, a galaxy's distance equals its velocity divided by the Hubble constant.

SOLUTION:

$$\text{Distance (in Mpc)} = \frac{\text{Velocity (in km/s)}}{\text{Hubble's constant (in km/s/Mpc)}} = \frac{100{,}000\ \text{km/s}}{70\ \text{km/s/Mpc}} = \frac{100{,}000}{70\ \text{Mpc}} = 1428\ \text{Mpc}$$

Remember, a megaparsec equals about 3.3 million light-years, so this galaxy is more than 4 billion light-years away. The light that we observe from such a distant galaxy began its trip about the time that our solar system was born. ●

Problems

1. In February 1987, a supernova was seen to explode in the Large Magellanic Cloud, a small galaxylike structure near the Milky Way galaxy. The supernova was about 170,000 light-years from Earth. (A light year is the distance light travels in 1 year. Take the speed of light to be 3×10^8 m/s.)
   a. How far away was this explosion in kilometers? In miles?
   b. When did this explosion actually occur?
   c. If it were somehow possible for you to drive your car along some stellar highway in the sky all the way to the location of this explosion, how long would it take you to get there, assuming you drove at 100 km/h (about 62 miles/h)?
2. Using the Sun as a standard candle, calculate the distance from the Sun to Venus if the energy detected per square meter on Venus is 2.89 kW/m^2. (Take the energy emitted by the Sun to be 4.24×10^{23} kW.)
3. Suppose that you observe a Cepheid variable to have a period of about 100 days and, hence, a luminosity of 6.4×10^{28} W. Suppose also that the amount of light you get from that star corresponds to an energy flow of about 2×10^{-14} W/m^2 at the location of your telescope. How far is that star from Earth?
4. What is the number of kilometers in 1 parsec? The number of miles?
5. Assuming a Hubble constant of 70 km/s/Mpc, what is the approximate velocity of a galaxy 10 Mpc away? 250 Mpc away? 5000 Mpc away?
6. If a galaxy is 700 Mpc away, how fast is it receding from us?
7. An observer on one of the raisins in our bread-dough analogy measures distances and velocities of neighboring raisins. The data are listed next:

Distance (cm)	**Velocity (cm/h)**
0.5	1.02
0.9	2.00
1.4	2.90
2.1	4.05
3.0	5.90
3.4	7.10

   Plot these data on a graph and use the plot to estimate a Hubble constant for the raisins.
8. From the data in Problem 7, estimate the time that has elapsed since the dough started rising. Estimate the largest and smallest values of this number consistent with the data.
9. Some theories say that during the inflationary period, the scale of the universe increased by a factor of 10^{50}. Suppose your height were to increase by a factor of 10^{50}. How tall would you be? Express your answer in light-years and compare it to the size of the observable universe, which is roughly 30 billion light-years across.
10. Suppose a proton (diameter about 10^{-13} cm) were to inflate by a factor of 10^{50}. How big would it be? Convert the answer to light-years and compare it to the size of the observable universe, which is roughly 30 billion light-years across.
11. How fast is a galaxy 5 billion light-years from Earth moving away from us? What fraction of the speed of light is this?

Investigations

1. The Milky Way is a band of stars that, as seen from Earth in the summer months, stretches all the way across the sky. Given what you know about galaxies, why do you suppose that our own galaxy appears this way to us? Who was the first natural philosopher to figure this out?
2. Will the constellation Andromeda be above the horizon tonight? If so, go out and try to spot the Andromeda galaxy.
3. Look up the "Great Attractor." How does the existence of such an object fit in with the concept of the Hubble expansion? How would you modify the raisin-bread dough analogy to put in the Great Attractor?
4. Investigate the cosmologies of other societies. How do they think the universe began? Do they predict how it will end?
5. What agencies or organizations fund cosmological research? What was the role of the Carnegie Institution of Washington in Edwin Hubble's research?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://universeadventure.org/** The Contemporary Physics Education Project (CPEP) *Universe Adventure,* by Lawrence Berkeley National Laboratory.

2. **http://map.gsfc.nasa.gov/m_uni.html** *Cosmology: The Study of The Universe,* a NASA site tutorial and collection of NASA educational resources and sites on cosmology.
3. **http://www.time.com/time/time100/scientist/profile/hubble.html** The Edwin Hubble biography from *Time* magazine.
4. **http://www.damtp.cam.ac.uk/user/gr/public/bb_cosmo.html** *A Brief History of Observational Cosmology,* from Cambridge University.
5. **http://www.pbs.org/wnet/hawking/html/home.html** A rich site to accompany *Stephen Hawking's Universe,* a PBS special.
6. **http://www.astro.ubc.ca/people/scott/cmb.html** *The Cosmic Microwave Background,* from the University of British Columbia.
7. **http://imagine.gsfc.nasa.gov/docs/science/mysteries_l1/origin_destiny.html** Origin and Destiny of the Universe, from NASA's *Imagine the Universe.*