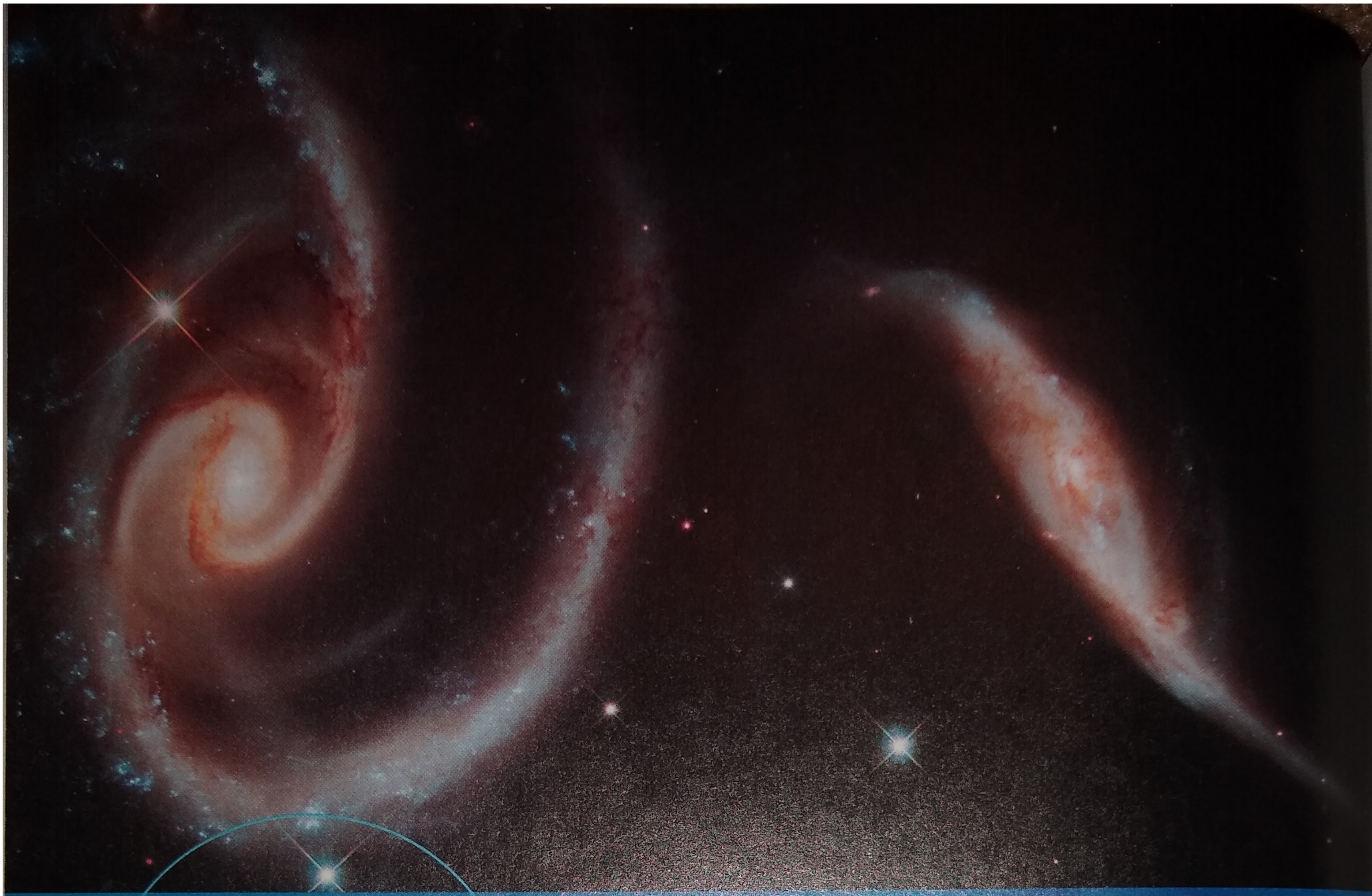


21

GALAXY EVOLUTION

LEARNING GOALS

21.1 LOOKING BACK THROUGH TIME

- How do we observe the life histories of galaxies?
- How do we study galaxy formation?

21.2 THE LIVES OF GALAXIES

- Why do galaxies differ?
- What are starbursts?

21.3 QUASARS AND OTHER ACTIVE GALACTIC NUCLEI

- How are quasars powered?
- Do supermassive black holes really exist?
- How do quasars let us study gas between the galaxies?

> *Reality provides us with facts so romantic that imagination itself could add nothing to them.*
>
> —Jules Verne

The spectacle of galaxies strewn like beautiful islands across the universe invites us to ponder their origins. What processes create the majestic spiral arms seen in many galaxies, and the elliptical or irregular shapes of others?

If we look closely, we see even more spectacular sights. Some galaxies are engaged in titanic collisions with others, sometimes leading to tremendous bursts of star formation in which new stars are born and massive stars explode 100 times as frequently as in the Milky Way. Other galaxies appear to harbor supermassive black holes surrounded by accretion disks that generate extraordinary luminosities. Narrow streams of matter jet at nearly the speed of light from a few of these galaxies into intergalactic space.

The origins of galaxies and the incredible phenomena they exhibit puzzled astronomers for much of the 20th century, but we are beginning to understand how galaxies evolve. In this chapter, we will sift through the fascinating clues that hint at how galaxies formed and developed, pausing now and again to admire the fantastic spectacles that we have uncovered in our quest for understanding.

21.1 LOOKING BACK THROUGH TIME

In Chapter 20, we saw how the distances to galaxies are measured and how such measurements revealed the expansion of our universe. We also saw how the expansion rate indicates an age for the universe of about 14 billion years. With that understanding, we are now ready to turn our attention to the study of how galaxies form and develop in our expanding universe—a subject known as **galaxy evolution.**

As we study how galaxies evolve, keep in mind that we would not be here if not for the galaxy-wide recycling processes that have gradually transformed the Milky Way's primordial gases into stars and planets [**Section 19.2**]. The same type of star–gas–star cycle has operated for at least some period of time in the history of all galaxies, so the differences we observe among galaxies provide clues to how individual galaxies form and evolve. Throughout this chapter, we will develop a deeper understanding of our cosmic origins by exploring both how galaxies first formed and how they can end up looking so different from one another. We'll begin in this section by considering how we study the lives of galaxies.

How do we observe the life histories of galaxies?

Observational evidence about the lives of galaxies comes from deep images of the universe, such as the Hubble Deep Field and the Hubble Ultra Deep Field (see Figure 20.1 and page 1). Remember that we can use powerful telescopes as time machines to observe the life histories of galaxies—the farther we look into the universe, the further we can see back in time [**Section 1.1**]. The most distant galaxies we observe have a lookback time of more than 13 billion years, meaning that we are seeing them as they were when the universe was less than a billion years old. Because we can see starlight from those galaxies, they must already have had some stars in place at that time, which is also about the time that the oldest stars in our own galaxy formed. It therefore seems safe to assume that many galaxies began to form at about this time, in which case those galaxies today are roughly the same age as the Milky Way.

This fact creates a linkage between a galaxy's distance and age that gives us a remarkable ability: Simply by photographing galaxies at different distances, we can assemble "family albums" of galaxies in different stages of development. Pictures of the most distant galaxies show galaxies in their childhood, and pictures of the nearest show mature galaxies as they are today. **FIGURE 21.1** shows partial family albums for elliptical, spiral, and irregular galaxies. Each individual photograph shows a single galaxy at a single stage in its life, and measuring the redshift of each galaxy allows us to place it on a timeline of the universe. Grouping these photographs by galaxy type then allows us to see how galaxies of a particular type have changed through time.

THINK ABOUT IT

We've used the word *today* in a very broad sense. For example, a relatively nearby galaxy may be located, say, 20 million light-years away, so we see it as it was 20 million years ago. In what sense is this "today"? (*Hint:* Compare 20 million years with the age of the universe.)

The photographs in Figure 21.1, taken by the Hubble Space Telescope, show galaxies extending back to a time when the universe was just 1 or 2 billion years old. However, we suspect that the first stars and galaxies formed even earlier. Observing these first stars and galaxies is a challenge not even Hubble can meet. Detecting such faraway galaxies will require larger telescopes, and the extreme redshifts expected for such galaxies mean that the telescopes will need to be particularly sensitive to infrared light. NASA hopes to launch a much larger infrared-sensitive successor to the Hubble Space Telescope (called the James Webb Space Telescope) in 2018, but for now we have little direct information about galaxy birth.

How do we study galaxy formation?

Observations allow us to learn a great deal about the evolution of galaxies, but we cannot yet see all the way back to the time when galaxies started to form. We must therefore use theoretical modeling to study the earliest stages of galaxy evolution. The most successful models for galaxy formation start from two key assumptions, both of which are backed by strong observational evidence [**Section 22.2**]:

- Hydrogen and helium gas filled all of space *almost* uniformly when the universe was very young—say, in the first million years after its birth.
- However, the distribution of matter was not *perfectly* uniform—certain regions of the universe started out ever so slightly denser than others, and these enhanced-density regions served as "seeds" for the formation of galaxies.

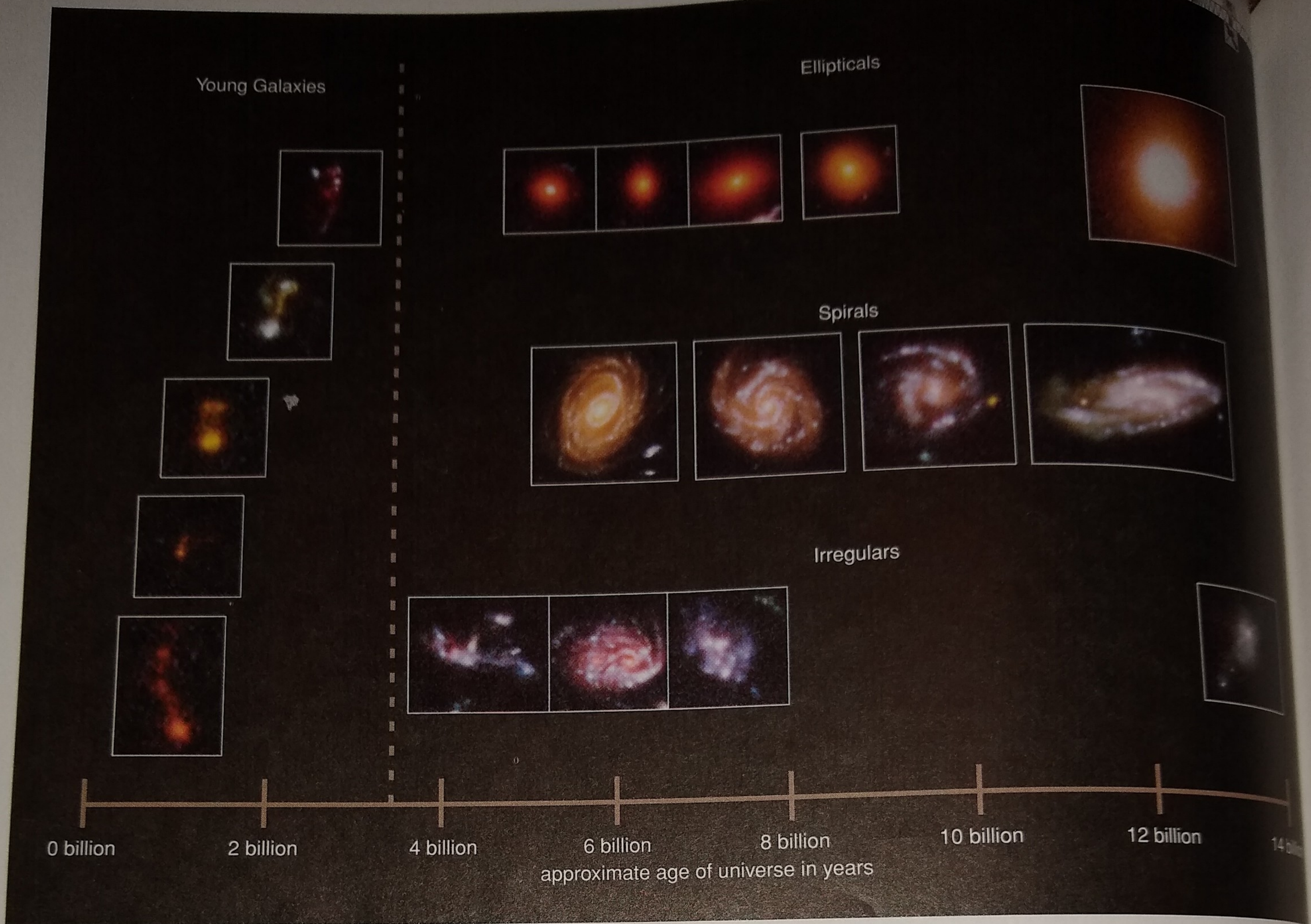


FIGURE 21.1 Family albums for elliptical, spiral, and irregular galaxies of different ages, plus some very young galaxies shown on the far left. These photos are all zoomed-in images of galaxies from the Hubble Ultra Deep Field, part of which is shown on page 1. We see more distant galaxies as they were when they were younger; the approximate age of the universe is indicated along the horizontal axis.

Beginning from these assumptions, we can model galaxy formation using well-established laws of physics to trace how the denser regions in the early universe grew into galaxies (**FIGURE 21.2**). The models show that the regions of enhanced density originally expanded along with the rest of the universe. However, the slightly greater pull of gravity in these regions gradually slowed their expansion. Within about a billion years, the expansion of these denser regions halted and reversed, and the material within them began to contract into *protogalactic clouds* like the clouds of matter that eventually formed our Milky Way [**Section 19.3**].

According to the models, the systems of protogalactic clouds that eventually formed spiral galaxies initially cooled as they contracted, radiating away their thermal energy, and the first generation of stars grew from the densest, coldest clumps of gas. These first-generation stars were probably quite massive [**Section 16.1**], living and dying within just a few million years—a short time compared with the time required for the collapse of protogalactic clouds into a spiral disk. The supernovae of these massive stars seeded the galaxy with its first sprinkling of heavy elements and generated shock fronts that heated the surrounding interstellar gas. This heating slowed the collapse of the protogalactic clouds and the rate at which stars formed within them, allowing time for additional gas to collect in each newly formed galaxy and then settle into a rotating disk.

This picture explains many of the basic features of galaxies. In particular, it explains why other spiral galaxies have the same basic structure as the Milky Way: a *disk population* of stars that orbit the galactic center in a fairly flat plane and a *spheroidal population* of stars with more randomly oriented orbits (see Figure 19.2). The spheroidal population consists of stars that were born before the galaxy's rotation became organized, which is why they have randomly oriented orbits around the galactic center. The disk population consists of stars born after the galaxy's gas settled into a rotating disk, which is why they all have similar orbits around the center of the galaxy (see Figure 19.18).

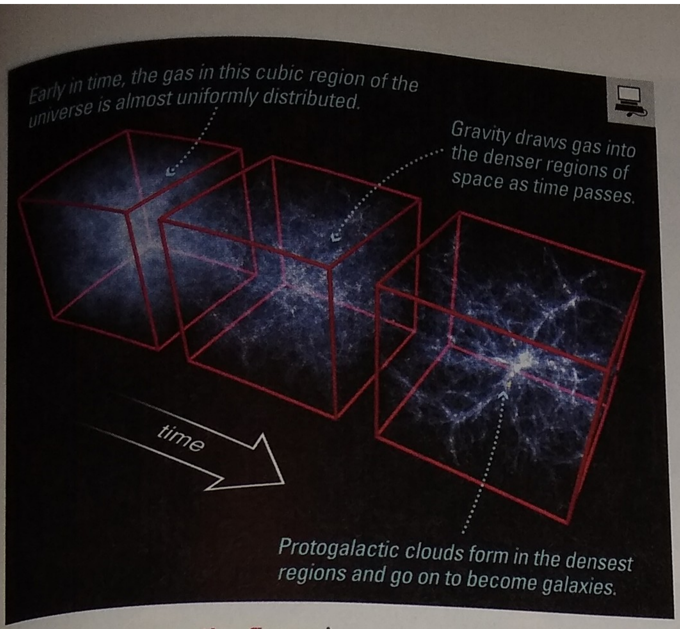


FIGURE 21.2 interactive figure A computer simulation of the formation of protogalactic clouds. The simulated region of space is about 500 million light-years wide and goes on to form numerous simulated galaxies.

However, this basic picture leaves at least two major questions unanswered. First, our models assume that galaxies formed in regions of slightly enhanced density, but they do not tell us where these density enhancements came from. The origin of density enhancements in the early universe is one of the major puzzles in astronomy, and we'll revisit it in Chapters 22 and 23. Second, our basic picture explains the origin of spiral galaxies quite well, but it does not tell us why some galaxies are elliptical and others irregular. That is the question to which we turn our attention next.

21.2 THE LIVES OF GALAXIES

The distinct differences between spiral, elliptical, and irregular galaxies clearly tell us that their life stories are not the same. We would like to tell the life story of each type of galaxy from beginning to end as completely as we told the life stories of stars, but many aspects of galaxy evolution remain mysterious and subject to active, ongoing research. Nevertheless, we now know the general outline of galactic life stories, and we have some promising ideas about why galaxies come in different types. In this section, we'll examine some of those ideas and show how they fit into the overall picture of galaxy evolution, even though the picture itself is not yet complete.

Why do galaxies differ?

Our best models for galaxy formation suggest that all galaxies began their lives in the same basic way, with gravity pulling matter into patches of the universe that were slightly denser than their surroundings. Those patches then contracted into protogalactic clouds, began to form stars, and assembled into galaxies. How, then, did they end up in the different types we see today? More specifically, why do spiral galaxies have gas-rich disks, while elliptical galaxies do not? Our models suggest two general categories of answer: (1) Galaxies may have ended up looking different because they began with slightly different birth conditions in their protogalactic clouds, or (2) galaxies may have begun their lives similarly but later changed through interactions with other galaxies.

Birth Conditions The first general category of explanation for the differences between spiral galaxies and elliptical galaxies traces a galaxy's type back to the protogalactic clouds from which it formed. Two factors may play a role:

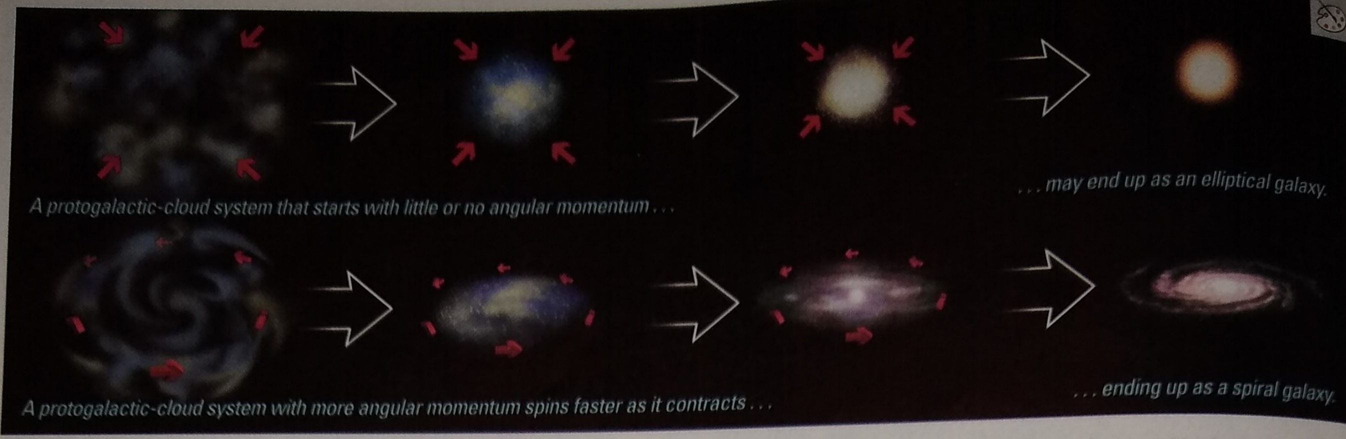
- **Protogalactic rotation** (FIGURE 21.3a). A galaxy's type might be determined in part by the rotation of the protogalactic-cloud system from which it formed. If the original system had a significant amount of angular momentum, it would have rotated quickly as it collapsed. The galaxy it produced would therefore have tended to form a disk, and the resulting galaxy would be a spiral galaxy. If the protogalactic-cloud system had little or no angular momentum, its gas might not have formed a disk at all, and the resulting galaxy would be elliptical.

- **Protogalactic density** (FIGURE 21.3b). A galaxy's type might also be determined in part by the density of the protogalactic clouds from which it formed. Protogalactic clouds with relatively high gas density would have radiated energy more effectively and cooled more quickly, thereby allowing more rapid star formation. If the star formation proceeded fast enough, all the gas could have been turned into stars before any of it had time to settle into a disk. The resulting galaxy would therefore lack a disk, making it an elliptical galaxy. In contrast, lower-density clouds would have formed stars more slowly, leaving plenty of gas to form the disk of a spiral galaxy.

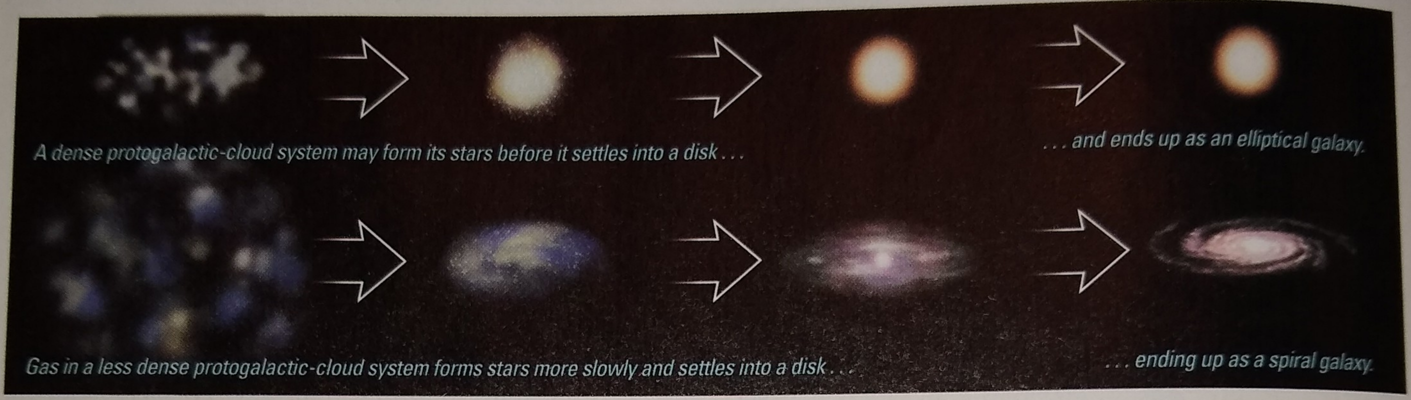
Evidence for the role of birth conditions comes from a few giant elliptical galaxies at very great distances. These galaxies look very red even after we have accounted for their large redshifts (FIGURE 21.4). They apparently have no blue or white stars at all, indicating that new stars no longer form within these galaxies—even though we are seeing them as they were when the universe was only a few billion years old. This finding suggests that all the stars in these elliptical galaxies formed almost simultaneously and very early in the history of the universe, which is consistent with the idea that all the stars formed before a disk could develop.

Later Interactions Differences in birth conditions probably play an important role in the overall story of why some galaxies have gas-rich disks and others do not. However, they probably are not the whole story, because they ignore one key fact: Galaxies rarely evolve in perfect isolation.

Think back to our scale model solar system in Chapter 1. On a scale on which the Sun was the size of a grapefruit, the nearest star was like another grapefruit a few thousand kilometers away. Because the average distances between stars are so huge compared to the sizes of stars, collisions between stars are extremely rare. However, if we rescale the universe so that



a The angular momentum of a galaxy's protogalactic-cloud system may determine whether it ends up spiral or elliptical.



b The gas density of a galaxy's protogalactic clouds may determine whether it ends up spiral or elliptical.

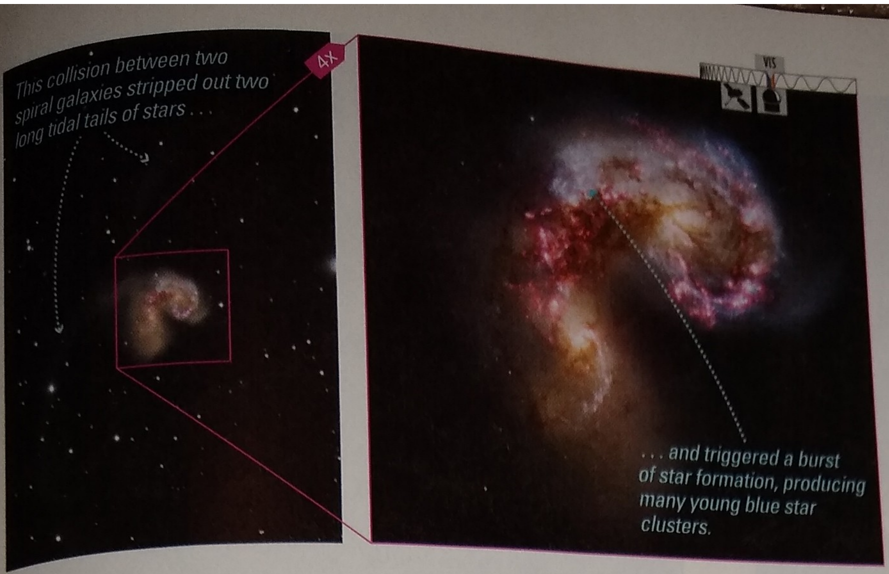
FIGURE 21.3 **interactive figure** These diagrams show two ways in which a galaxy's birth conditions may have determined whether it ended up spiral or elliptical.

our *galaxy* is the size of a grapefruit, the Andromeda Galaxy is like another grapefruit only about 3 meters away, and a few smaller galaxies lie considerably closer. In other words, the average distances between galaxies are not much larger than the sizes of galaxies, meaning that collisions between galaxies are inevitable. Our own Milky Way Galaxy is not immune. About 80,000 light-years away from us, directly behind the galactic bulge, a small elliptical galaxy (the Sagittarius Dwarf [**Section 19.1**]) is currently crashing through the Milky Way's disk.

Collisions between galaxies are spectacular events that unfold over hundreds of millions of years (**FIGURE 21.5**). During our short lifetimes, we can at best see a snapshot of a collision in progress, distorting the shapes of the colliding galaxies. Galactic collisions must have been even more frequent in the distant past, when the universe was smaller and galaxies were closer together. Observations confirm that distorted-looking galaxies—probably galaxy collisions in progress—were more common in the early universe than they are today (**FIGURE 21.6**).

We can learn much more about galactic collisions with the aid of computer simulations, which allow us to "watch" collisions that in nature take hundreds of millions of years to unfold. These computer models show that a collision between two spiral galaxies can create an elliptical galaxy (**FIGURE 21.7**). Tremendous tidal forces between the colliding

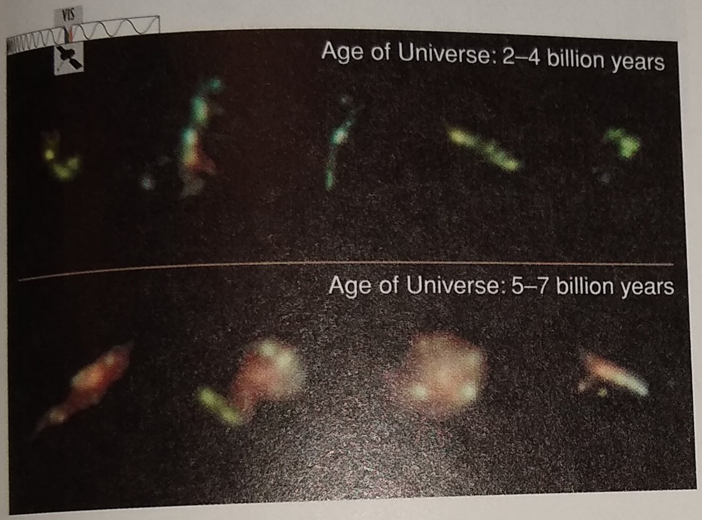
FIGURE 21.4 The light we observe from the distant elliptical galaxy called HUDF-JD2 (circled) left that galaxy when the universe was about 800 million years old. Even though it is very young, the galaxy contains about eight times as many stars as the Milky Way, and its color indicates that few new stars are forming within it.



This collision between two spiral galaxies stripped out two long tidal tails of stars . . .

. . . and triggered a burst of star formation, producing many young blue star clusters.

FIGURE 21.5 A pair of colliding spiral galaxies known as the Antennae (NGC 4038/4039). The image taken from the ground (left) reveals their vast tidal tails, while the close-up from the Hubble Space Telescope shows the burst of star formation at the center of the collision.



Age of Universe: 2–4 billion years

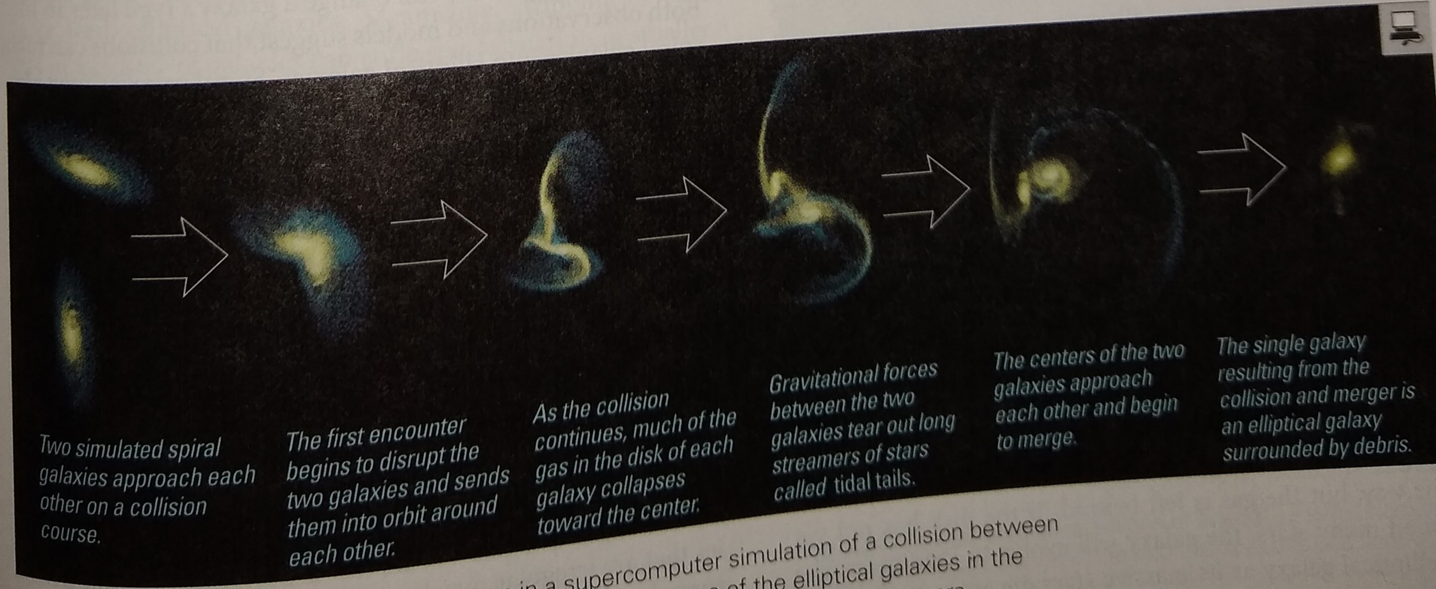
Age of Universe: 5–7 billion years

FIGURE 21.6 These Hubble Space Telescope photographs offer a zoomed-in view of some of the young galaxies from the Hubble Deep Field (see Figure 20.1). Notice that these galaxies do not look like either the spiral or the elliptical galaxies that are common in the present-day universe, and instead appear to be undergoing collisions. We infer that galaxy collisions were much more common in the early universe than they are today.

galaxies tear apart the two disks, randomizing the orbits of their stars. Meanwhile, a large fraction of their gas sinks to the center of the collision and rapidly forms new stars. Supernovae and stellar winds eventually blow away the rest of the gas. When the cataclysm finally settles down, the merger of the two spirals has produced a single elliptical galaxy. Little gas is left for a disk, and the orbits of the stars have random orientations.

Galaxies in Clusters Observations of galaxies in clusters support the idea that at least some elliptical galaxies result from collisions and subsequent mergers. Elliptical galaxies dominate the galaxy populations at the cores of dense clusters of galaxies, where collisions should be most frequent. This fact may mean that any spirals once present became ellipticals through collisions.

Stronger evidence comes from structural details of elliptical galaxies, which often attest to a violent past. Some elliptical galaxies have stars and gas clouds with orbits suggesting that they are leftover pieces of galaxies that merged in a



Two simulated spiral galaxies approach each other on a collision course.

The first encounter begins to disrupt the two galaxies and sends them into orbit around each other.

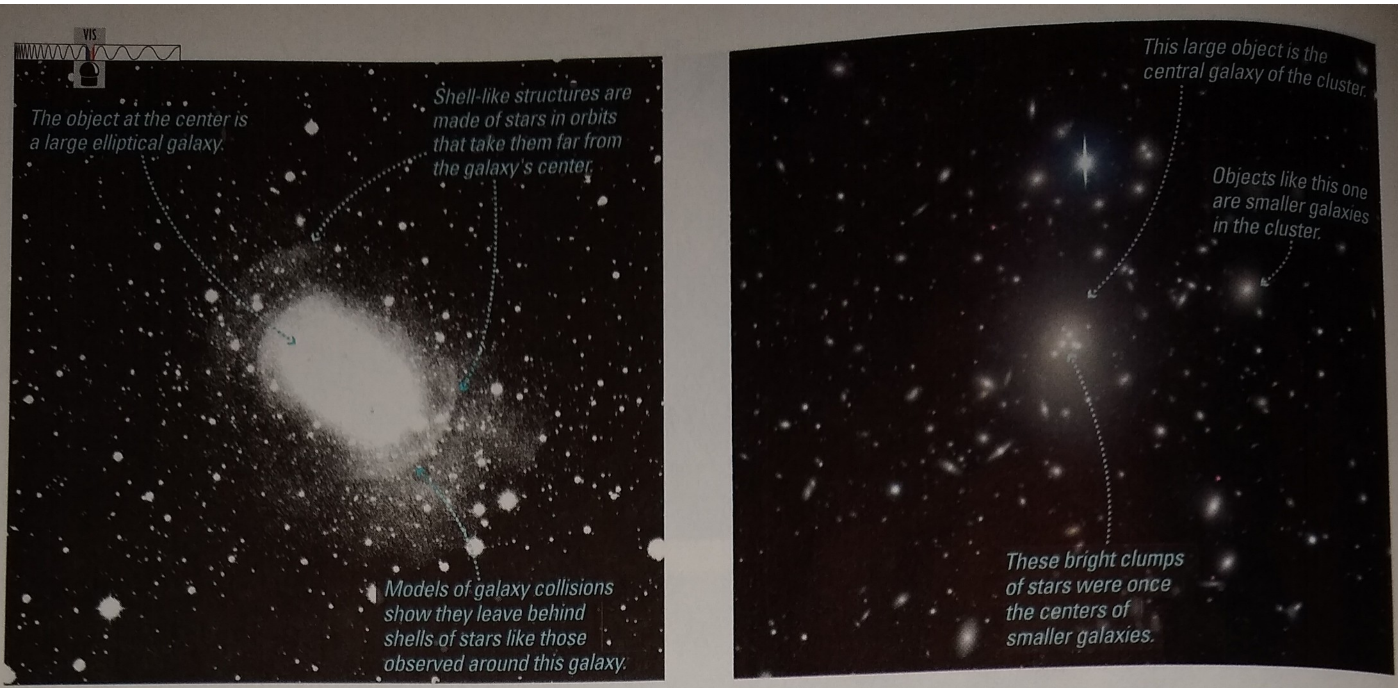
As the collision continues, much of the gas in the disk of each galaxy collapses toward the center.

Gravitational forces between the two galaxies tear out long streamers of stars called tidal tails.

The centers of the two galaxies approach each other and begin to merge.

The single galaxy resulting from the collision and merger is an elliptical galaxy surrounded by debris.

FIGURE 21.7 interactive figure Several stages in a supercomputer simulation of a collision between two spiral galaxies that results in an elliptical galaxy. At least some of the elliptical galaxies in the present-day universe formed in this way. The whole sequence spans about 1.5 billion years.



a The central region of elliptical galaxy NGC 3923 is surrounded by several distinct shells of stars. These stars probably formed after gas was stripped out of the galaxy during a past collision.

b This image shows the central dominant galaxy of the cluster Abell 3827, which has apparently grown by consuming smaller galaxies that have collided with it. Notice that the center of this galaxy contains multiple clumps of stars that probably once were the centers of individual galaxies.

FIGURE 21.8 Evidence for past collisions in elliptical galaxies.

past collision. One example is the elliptical galaxy NGC 3923, shown in **FIGURE 21.8a**. Although it is not a member of a cluster, this galaxy's unusual structure is probably the result of a collision. The shells surrounding this galaxy are made of stars on orbits that are hard to explain if the entire galaxy came from a single protogalactic cloud. The stars that we see in the shells probably plunge back and forth through the central part of the galaxy, swinging from one side to the other like a pendulum. The shells represent the extreme ends of these plunging orbits, where the stars spend most of their time.

The most decisive evidence that collisions affect the evolution of elliptical galaxies comes from observations of the **central dominant galaxies** found at the centers of many dense clusters. Central dominant galaxies are giant elliptical galaxies that apparently grew to huge sizes by consuming other galaxies through collisions. They frequently contain several tightly bound clumps of stars that probably were the centers of individual galaxies before being swallowed by the giant (**FIGURE 21.8b**). This process of *galactic cannibalism* can create central dominant galaxies more than 10 times as massive as the Milky Way, making them the most massive galaxies in the universe.

Observations of galaxy clusters also suggest yet another mechanism by which spiral galaxies might become ellipticals. The central regions of dense galaxy clusters tend to be filled with very hot gas [**Section 23.2**]. When a spiral galaxy cruises through the center of such a cluster, the hot gas exerts drag forces that slow the galaxy's gas but not its stars. The galaxy's stars therefore continue to move freely along their way, but the gas is left behind. If the disk has not yet formed many stars, the galaxy will evolve to look more like an elliptical galaxy as its massive stars die away. Its disk will fade, while its bulge and halo will remain prominent. If the disk has already formed a large number of stars when its gas is stripped, the remaining galaxy will look like a spiral galaxy without its gaseous disk, which makes it a *lenticular galaxy* (see Figure 20.5).

An Incomplete Answer We have discussed several factors that can affect a galaxy's type. In some cases, a galaxy's type may be determined at birth, by either the rotation rate or the density of the galaxy's protogalactic cloud. If the protogalactic cloud began with either unusually slow rotation or unusually high density, the result may be an elliptical galaxy; otherwise, it will be a spiral galaxy. In other cases, interactions between galaxies can change a galaxy's type later in life. Both observations and models suggest that collisions can turn spiral galaxies into elliptical galaxies. Spiral galaxies may also have their disks stripped of cool gas as they pass through the hot gas in the central regions of galaxy clusters.

Birth conditions and subsequent interactions probably both play important roles in galaxy evolution, although we are not yet certain which is more influential. Nevertheless, when we consider both kinds of mechanisms together, they do seem to account for the basic differences between galaxy types. The formation scenarios explain why the vast majority of galaxies are either spiral or elliptical in shape. The interaction scenarios explain why ellipticals are more common in clusters while spirals are more common outside clusters, and gas stripping may explain why we see significant numbers of lenticular galaxies. Even the relatively small fraction of galaxies that are irregular may be explained by these ideas: At least some irregulars probably are galaxies undergoing some sort of disruptive interaction.

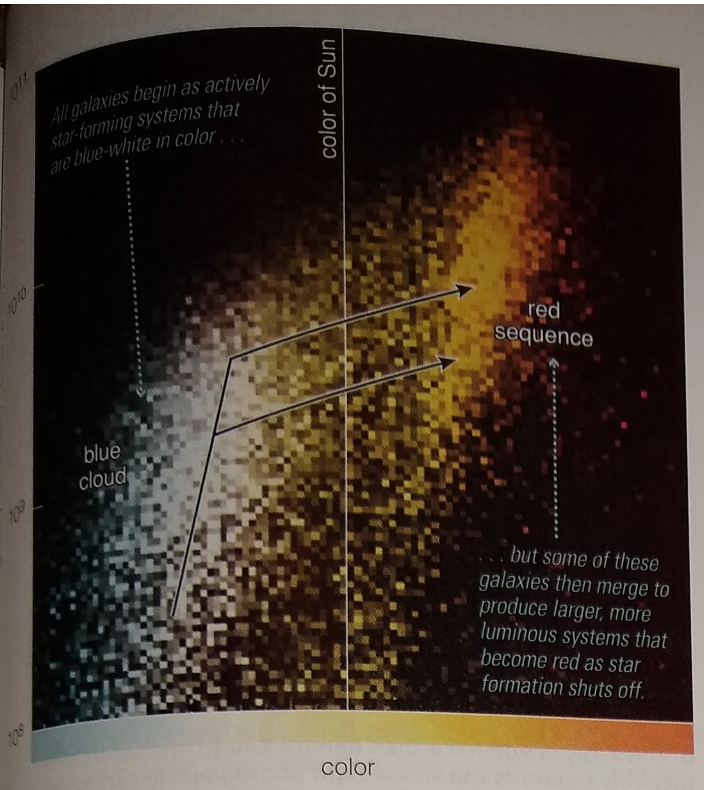


FIGURE 21.9 Galaxy evolution in color and luminosity. This figure schematically shows how the relationships between galaxy color and luminosity are thought to arise. All galaxies begin as active star-forming systems in the *blue cloud*. Mergers of these galaxies can produce larger galaxies, some of which cease forming new stars. Others may stop forming stars because their gas was stripped away after they entered a galaxy cluster. The galaxies without active star formation become redder in color as their stellar populations age, shifting them onto the *red sequence* of the diagram.

The general trend is therefore for galaxies to begin as active star-forming systems that can grow larger as they collide and merge with other galaxies. In some cases, these collisions and mergers ultimately lead to large elliptical galaxies in which star formation has ceased. **FIGURE 21.9** illustrates how this trend is thought to affect the relationship between galaxy color and galaxy luminosity. As time progresses, we expect galaxy mergers to produce an increasing number of large, red, elliptical galaxies. Meanwhile, stripping of cool gas in a cluster of galaxies can stifle star formation in smaller galaxies, causing some of them to become red as well.

What are starbursts?

Our discussion so far has focused on the fact that spiral galaxies generally have a star–gas–star cycle that supports ongoing star formation at a fairly steady rate, while elliptical galaxies generally contain only stars that formed in the distant past. However, observations show that a small percentage of galaxies in the present-day universe don't fit either pattern of star formation; instead, they are forming stars at an astonishingly rapid rate. These **starburst galaxies** may represent a stage of evolution that many galaxies have gone through at least once during their lives.

A starburst must be a temporary stage in a galaxy's life because the rates of star formation in starburst galaxies are unsustainable. For example, the Milky Way Galaxy produces an average of about one new star per year, a rate that will allow the galactic disk to retain interstellar gas and continue star formation until long after the Sun has died. In contrast, some starburst galaxies form new stars at rates exceeding 100 stars per year—a rate that would consume all of a galaxy's interstellar gas in just a few hundred million years. A starburst therefore can last no longer than this; after its starburst is over, a starburst galaxy presumably returns to a spiral, elliptical, or irregular state. Let's look a little more closely at this spectacular but temporary stage of galaxy evolution.

Observations of Starburst Galaxies The impressive rates of star formation in starburst galaxies were generally recognized only about three decades ago. These voracious consumers of interstellar gas look peculiar at visible wavelengths because they are filled with star-forming molecular clouds, which conceal much of the action. Dust grains in the molecular clouds absorb most of the visible and ultraviolet radiation streaming from the many hot, young stars of a starburst galaxy.

Astronomers didn't recognize the nature of starburst galaxies until they began to study them in long-wavelength infrared light—light that can be observed only with telescopes in space. Starburst galaxies emit strongly in the infrared because of their interstellar dust. The visible and ultraviolet radiation from a starburst galaxy's many hot, young stars heats its dust grains to higher temperatures than we find for dust in the Milky Way, and the dust ultimately re-emits all this absorbed energy as infrared light. **FIGURE 21.10** shows an infrared image of an especially luminous starburst galaxy, along with its spectrum from visible through infrared wavelengths. Note that the visible output of this galaxy is about 10 billion solar luminosities ($10^{10}L_{\text{Sun}}$), not very different from the total luminosity of the Milky Way. However, its infrared output is a trillion times that of our Sun ($10^{12}L_{\text{Sun}}$), making it 100 times brighter in infrared light than in visible light.

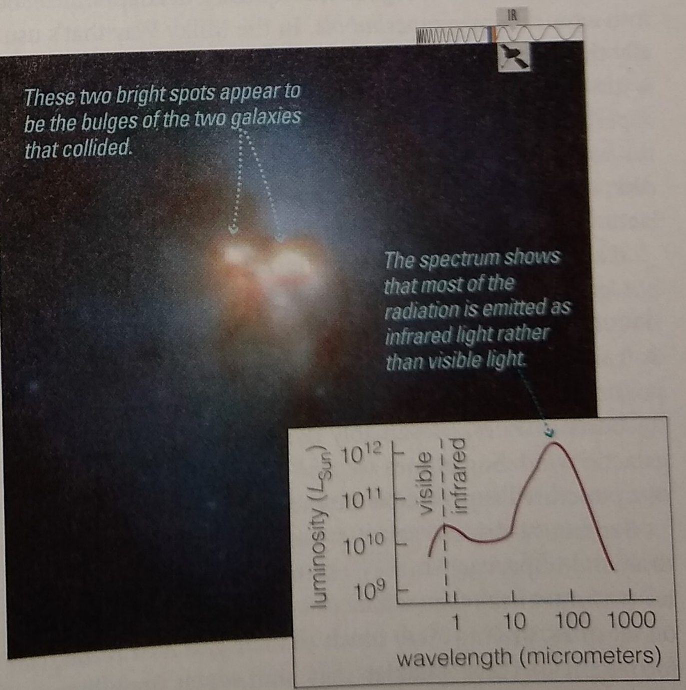


FIGURE 21.10 Infrared observations of Arp 220, a large starburst galaxy. (The region shown in the photo is about 10,000 light-years across.)

a This visible-light photograph (from the Hubble Space Telescope) shows violently disturbed gas (red) blowing out both above and below the disk.

b This X-ray image from the Chandra X-Ray Observatory shows the same region as the visible-light photograph in part a. The reddish region represents X-ray emission from very hot gas blowing out of the disk. The bright dots in the galactic disk probably represent X-ray emission from accretion disks around black holes or neutron stars produced by recent supernovae.

FIGURE 21.11 **interactive photo** Visible-light and X-ray views of a starburst galaxy called M82, showing its galactic wind. Both images show the same region, which is about 16,000 light-years across.

Galactic Winds A star formation rate 100 times that of the Milky Way also means that supernovae will occur at 100 times the Milky Way's rate. Just as in the Milky Way, each supernova in a starburst galaxy generates a shock front that creates a *bubble* of hot gas [**Section 19.2**]. The shock fronts from several nearby supernovae quickly overlap and blend into a much larger *superbubble*. In the Milky Way that's usually the end of the story, but in a starburst galaxy the drama is just beginning. Supernovae continue to explode inside the superbubble, adding to its thermal and kinetic energy. When the superbubble starts to break through the disrupted gaseous disk, it expands even faster. Hot gas then erupts into intergalactic space, creating a **galactic wind**.

Galactic winds consist of low-density but extremely hot gas, typically with temperatures of 10–100 million K (FIGURE 21.11). They do not emit much visible light, but they do generate X rays. X-ray telescopes in orbit have detected pockets of X-ray emission surrounding the disks of some starburst galaxies, presumably coming from the outflowing galactic wind. Sometimes we also see the glowing remnants of a punctured superbubble extending out into space.

Supernova-driven galactic winds have an even more dramatic impact when they occur in small starburst galaxies (FIGURE 21.12). The winds can blow out of small galaxies on all sides, driving away much of their gas. As a result, star formation in these galaxies may shut down for billions of years. Some of the small elliptical galaxies in the Local Group apparently have experienced bursts like this more than once during their lifetimes. Presumably, each of these bursts of star formation created enough supernovae to eject nearly all the gas that remained in the galaxy. Star formation was then put on hold for several billion years until enough gas could reaccumulate within the galaxy for a new starburst to ignite.

THINK ABOUT IT

Dwarf galaxies that have undergone bursts of star formation tend to have fewer heavy elements than large galaxies. Why do you think that is? (*Hint:* What happens to the heavy elements produced by the burst of star formation?)

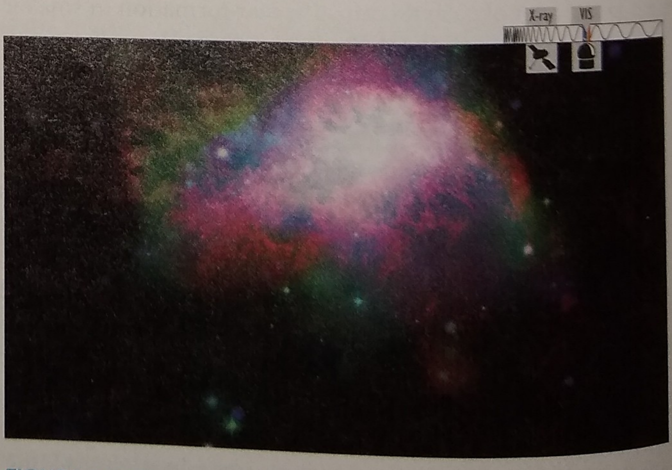


FIGURE 21.12 This X-ray/visible composite photo of dwarf starburst galaxy NGC 1569 shows hot gas blowing out in several different directions. X-ray light from this hot galactic wind is shown in blue, and visible light from disturbed hydrogen gas is shown in red.

Causes of Starbursts Many of the most luminous starburst galaxies appear to be violently disturbed, suggesting that a collision between galaxies triggered the starburst. For example, the colliding galaxy pair shown in Figure 21.5 is currently undergoing a starburst. The picture clearly shows many young, blue star clusters strewn amidst the dark, disturbed gas clouds. Starbursts therefore help explain why elliptical galaxies lack young stars and cool gas. The starburst uses up most of the cool gas; the galactic wind blows away what remains; and all the hot, massive stars die out within just a few hundred million years after the starburst ends. By the time the merger into an elliptical galaxy is complete, there is simply no cool gas left to support ongoing star formation.

The causes of smaller-scale starbursts are not yet clear. At least some small irregular galaxies look irregular because they are currently undergoing collisions and starbursts, but not all irregular galaxies are colliding. For example, the Large Magellanic Cloud (which orbits the Milky Way) is an irregular galaxy that is also undergoing a period of rapid star formation. The starburst leading to this galaxy's irregular appearance might have been triggered not by a collision but rather by a close encounter with the Milky Way. No matter what their exact causes turn out to be, starbursts represent an important piece in the overall puzzle of galaxy evolution that astronomers will continue to study.

Black Holes Tutorial, Lessons 1, 2

21.3 QUASARS AND OTHER ACTIVE GALACTIC NUCLEI

Starbursts may be spectacular, but some galaxies display even more incredible phenomena: extreme amounts of radiation and sometimes powerful jets of material emanating from deep in their centers (FIGURE 21.13). These unusually bright galactic centers are called **active galactic nuclei**. The brightest active galactic nuclei are known as **quasars**, and they are fantastically luminous. The most powerful quasars produce more light than 1000 galaxies the size of the Milky Way.

Like starbursts, quasars are yet another temporary stage in the process of galaxy evolution. We find quasars primarily at great distances, telling us that these blazingly luminous objects were most common billions of years ago, when galaxies were in their youth. We find no quasars (and relatively few galaxies with any type of active galactic nucleus) nearby, and because nearby galaxies are older, we conclude that the objects that shine as quasars in young galaxies must become dormant as the galaxies age. Many nearby galaxies that now look quite normal must therefore have centers that once shone brilliantly as quasars. We do not yet know exactly how quasars tie in with the overall story of galaxy evolution, but mounting evidence suggests that the development of quasars is intimately connected with the growth of galaxi

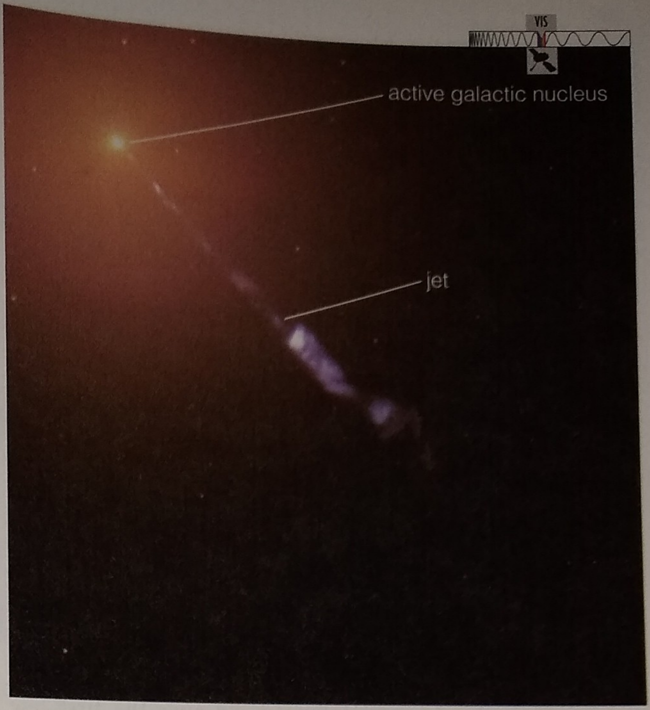


FIGURE 21.13 **interactive photo** The active galactic nucleus in the elliptical galaxy M87. The bright yellow spot is the active nucleus, and the blue streak is a jet of particles shooting outward from the nucleus at nearly the speed of light.

How are quasars powered?

What could possibly be the source of the incredible power outputs of quasars, and why did quasars fade away? Strong evidence points to a single answer: The energy output of a quasar comes from a gigantic accretion disk surrounding a **supermassive black hole**—a black hole with a mass millions to billions of times that of our Sun. The story of how scientists reached this remarkable conclusion begins with the discovery of quasars a half-century ago.

The Discovery of Quasars In the early 1960s, a young professor at the California Institute of Technology named Maarten Schmidt was busy identifying cosmic sources of radio-wave emission. Radio astronomers would tell him the coordinates of newly discovered radio sources, and he would try to match them with objects seen through visible-light telescopes. Usually the radio sources turned out to be normal-looking galaxies, but one day he discovered a major mystery: A radio source called 3C 273 looked like a blue star through a telescope, but had strong emission lines at wavelengths that did not appear to correspond to those of any known chemical element. (The designation 3C 273 stands for 3rd Cambridge Radio Catalogue, object 273.)

After months of puzzlement, Schmidt suddenly realized that the emission lines were not coming from an unfamiliar element, but were actually hydrogen emission lines that were hugely redshifted from their normal wavelengths (FIGURE 21.14). Schmidt calculated that the expansion of the universe was carrying 3C 273 away from us at 17% of the speed of light. He computed the distance to 3C 273 using Hubble's law, and from its distance and apparent brightness, he estimated its luminosity [**Section 15.1**]. What he found