Cau any 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.

MA 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 galaxies.

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

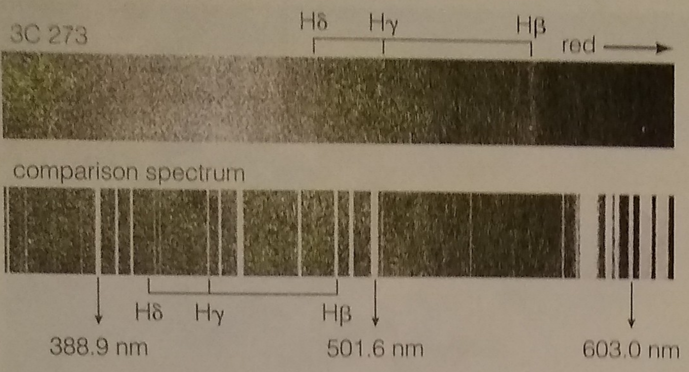

FIGURE 21.14 These two photographs show a spectrum of the quasar 3C 273 (top) and a comparison spectrum with spectral lines at their rest wavelengths (bottom). The lines labeled Hβ, Hγ, and Hδ are hydrogen emission lines. Note their significant redshift in the quasar spectrum relative to the comparison spectrum.

was astonishing: 3C 273 has a luminosity of about 10^{39} watts, or well over a trillion (10^{12}) times the luminosity of our Sun—making it hundreds of times more luminous than the entire Milky Way Galaxy. Discoveries of similar but even more distant objects soon followed. Because the first few of these objects were strong sources of radio emission that looked like stars through visible-light telescopes, they were named "quasi-stellar radio sources," or *quasars* for short. Astronomers later learned that most quasars are not such powerful radio emitters, but the name has stuck.

Most quasars lie more than halfway to the cosmological horizon [**Section 20.3**]. The lines in typical quasar spectra are shifted to more than three times their rest wavelengths, which tells us that the light from these quasars emerged when the universe was less than a third of its present age. The farthest known quasars shine with light that began its journey to Earth when the universe was less than 1 billion years old.

The extraordinary power output of quasars explains why they were at first so mysterious. These bright galactic centers emit so much light that they swamp the rest of the light from the galaxies that contain them, making the surrounding galaxies hard to detect. That is why quasars look "quasi-stellar." Moreover, while most stars and galaxies emit primarily visible light, quasars emit their energy across a wide swath of the electromagnetic spectrum, radiating approximately equal amounts of energy from infrared wavelengths all the way to gamma rays (**FIGURE 21.15**). This wide range of photon energies implies that quasars contain matter with a wide range of temperatures. Quasars also produce strong emission lines, allowing us to measure their redshifts.

Evidence from Nearby Active Galactic Nuclei

The power output and spectral characteristics of quasars gave us some hints about the power source of quasars, but gaining a deeper understanding required more detailed data. Quasars are difficult to study in detail because they are so far away. Luckily, some quasarlike objects are much closer to home. About 1% of present-day galaxies—that is, galaxies we see nearby—have active galactic nuclei that look very much like quasars, except that they are less powerful.* These objects have spectra that look much the same as quasar spectra with strong emission lines and energy radiated from infrared to gamma rays, suggesting that the same type of phenomenon is producing their spectra. However, because these active galactic nuclei are less luminous than quasars, the galaxies that surround them are easier to see.

The light-emitting regions of active galactic nuclei are so small that even the sharpest images do not resolve them. Our best visible-light images show only that active galactic nuclei must be smaller than 100 light-years across. Radio-wave images made with the aid of interferometry [**Section 6.4**] show that these nuclei are even smaller: less than a light-year across. Rapid changes in the luminosities of some active galactic nuclei point to an even smaller size.

To understand how variations in luminosity give us clues about an object's size, imagine that you are a master of the universe and you want to signal one of your fellow masters a billion light-years away. An active galactic nucleus would make an excellent signal beacon, because it is so bright. However, suppose the smallest nucleus you can find is 1 light-year across. Each time you flash it on, the photons from the front end of the source reach your fellow master a full year before the photons from the back end. If you flash it on and off more than once a year, your signal will be smeared out. Similarly, with a source that is 1 light-day across, you can transmit signals that flash on and off no more than once a day. If you want to send signals just a few hours apart, you need a source no more than a few light-hours across.

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*The galaxies that contain these active galactic nuclei are often called *Seyfert galaxies* after astronomer Carl Seyfert, who in 1943 grouped galaxies with active galactic nuclei into a special class.

FIGURE 21.15 This schematic quasar spectrum represents the average emission spectrum of many quasars. (The dashed portion of the spectrum represents wavelengths for which we lack good data.)

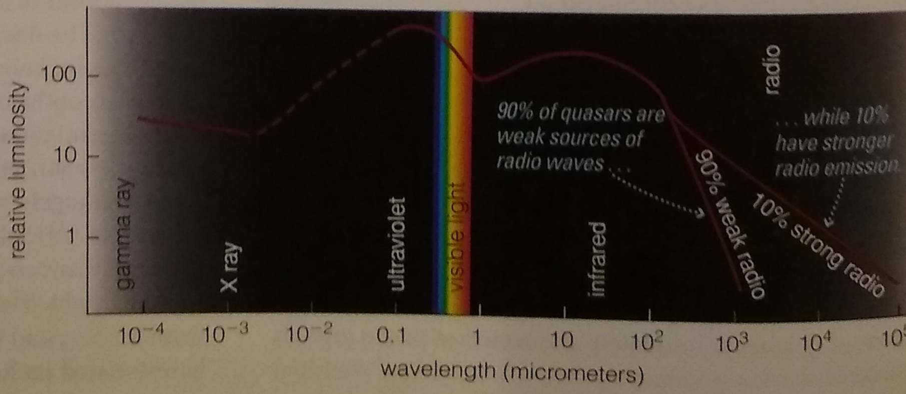

FIGURE 21.16 This image, made with the Very Large Array in New Mexico, shows radio-wave emission from the radio galaxy Cygnus A. Brighter regions represent stronger radio emission. Notice that the strongest emission comes from two radio lobes that lie far beyond the bounds of the galaxy that we see with visible light (inset photo), but the lobes are clearly connected to the central active galactic nucleus by two long jets of particles.

Occasionally, the luminosity of an active galactic nucleus doubles in a matter of hours. The fact that we see a clear signal indicates that the source must be less than a few light-hours across. In other words, *the incredible luminosities of active galactic nuclei and quasars are being generated in a volume of space not much bigger than our solar system.*

Radio Galaxies and Jets Another clue to the nature of quasars dates back to the early 1950s, a decade before the discovery of quasars. Radio astronomers noticed that certain galaxies, now called **radio galaxies**, emit unusually strong radio waves. Upon closer inspection, they learned that much of the radio emission comes not from the galaxies themselves but rather from pairs of huge *radio lobes,* one on either side of the galaxy. Today, radio telescopes resolve the structure of radio galaxies in vivid detail (**FIGURE 21.16**).

At the center of a radio galaxy we see emission from an active galactic nucleus less than a few light-years across. We often see two gigantic jets of plasma shooting out of the active galactic nucleus in opposite directions; both jets are easy to see in Figure 21.16, but some radio galaxies are oriented so that we can see only the jet tilted in our direction. Using time-lapse radio images taken several years apart, we can track the motions of various plasma blobs in the jets. Some of these blobs move at speeds close to the speed of light. The lobes lie at the ends of the jets, which are sometimes as far as a million light-years from the galactic center.

Putting all this information together gives us a basic picture of what occurs in a radio galaxy: The active galactic nucleus is the power source, and it drives two jets of particles that stream outward in opposite directions at nearly the speed of light. These jets shoot out far beyond the bounds of the stars in the radio galaxy, but they eventually ram into surrounding intergalactic gas. The places where the jets ram into the gas show up as the hot spots within radio lobes. The particles are then deflected from these hot spots to make the larger radio lobes, much as the spray of water from a fire hose is deflected when it hits a wall.

The relative prominence of the active galactic nucleus, jets, and lobes can vary greatly from one radio galaxy to another, largely because of differences in the luminosity of the nucleus and the densities of particles in the jets and the surrounding intergalactic gas. The shapes of the jets and lobes can also vary, especially if the galaxy is moving relative to surrounding intergalactic gas. **FIGURE 21.17** shows a small gallery of typical radio galaxies.

As a result of these observations, we now suspect that quasars and radio galaxies are the same types of objects viewed in slightly different ways. In fact, many quasars have jets and radio lobes like those seen in radio galaxies (**FIGURE 21.18**). Moreover, the active galactic nuclei of many radio galaxies seem to be concealed beneath donut-shaped rings of dark molecular clouds (**FIGURE 21.19**). Such structures may look like quasars when they are oriented so that we can see the active galactic nucleus at the center and look like the nuclei of radio galaxies when the ring of dusty gas dims our view of the central object.*

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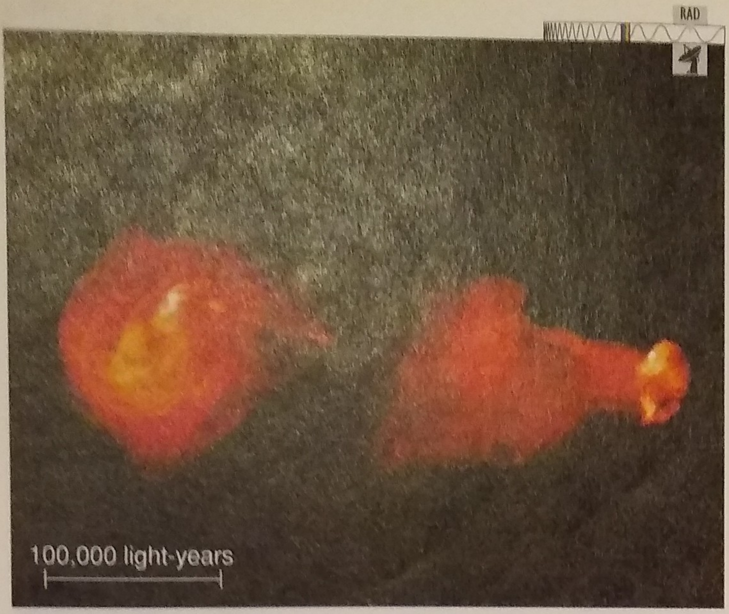
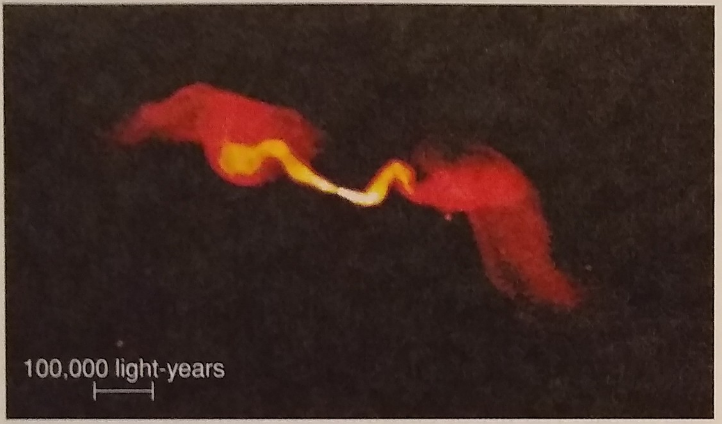
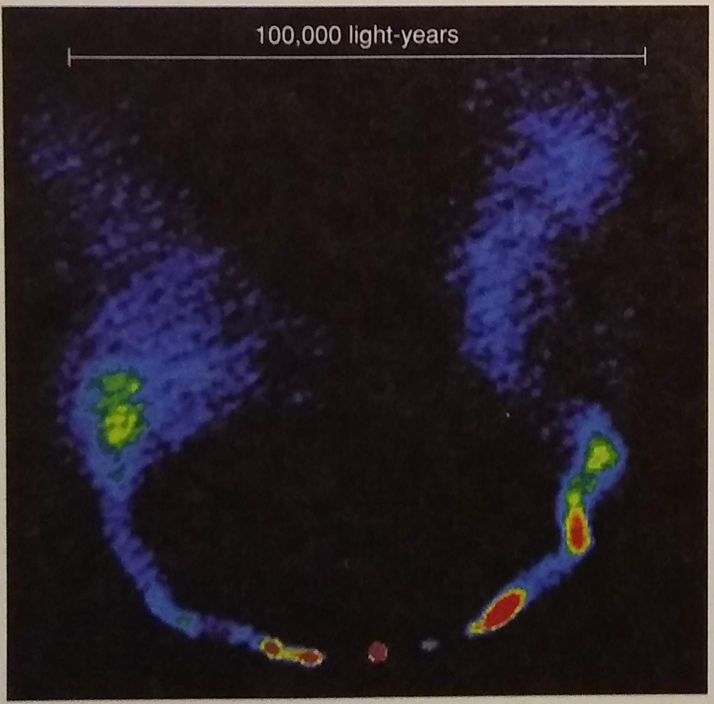
*A subset of active galactic nuclei called *BL Lac objects* (after the prototype object in the constellation Lacerta) are probably the centers of radio galaxies whose jets happen to point directly at us.



a Radio galaxy 3C 353.



b Radio galaxy 3C 31.



c Radio galaxy NGC 1265. The lobes are swept back because the galaxy is moving relative to the surrounding intergalactic gas.

FIGURE 21.17 Radio galaxy gallery. All three have double lobes, but very different shapes and sizes.

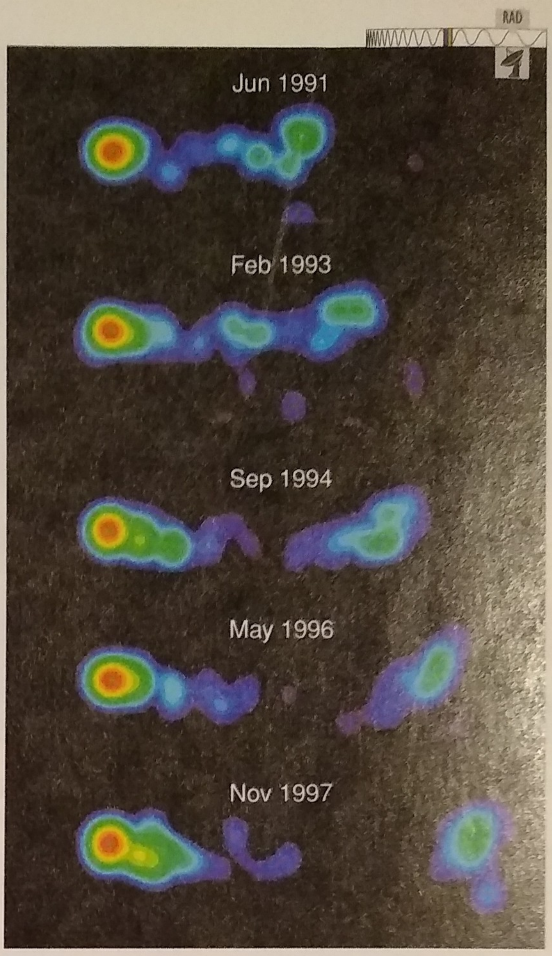


FIGURE 21.18 These radio images, taken over a period of several years, show a blob of plasma moving at almost the speed of light in a jet extending from the quasar 3C 345; the quasar is on the left in each image.

Supermassive Black Holes Astronomers have worked hard to envision physical processes that might explain how radio galaxies, quasars, and other active galactic nuclei release so much energy within such small central volumes. Only one explanation seems to fit: The energy comes from matter falling into a supermassive black hole.

The idea that the huge energy outputs of active galactic nuclei can be traced to supermassive black holes is much like the idea we used earlier to explain the emission from X-ray binary star systems [**Section 18.2**]. The gravitational potential energy of matter falling toward the black hole is converted into kinetic energy, and collisions between infalling particles convert the kinetic energy into thermal energy. The resulting heat causes this matter to emit the intense radiation we observe. As in X-ray binaries, we expect that the infalling matter swirls through an accretion disk before it disappears beneath the event horizon of the black hole (**FIGURE 21.20**). However, in order to produce the enormous luminosity of a quasar, an amount of matter greater than that of the Sun needs to pass through the accretion disk and fall into the black hole each year.

If the supermassive black hole model is correct, it should be able to explain the major observed features of quasars and other active galactic nuclei. In particular, it should explain their extreme luminosities, the fact that they emit radiation over a broad range of wavelengths from radio waves to X rays, and the presence of their powerful jets.

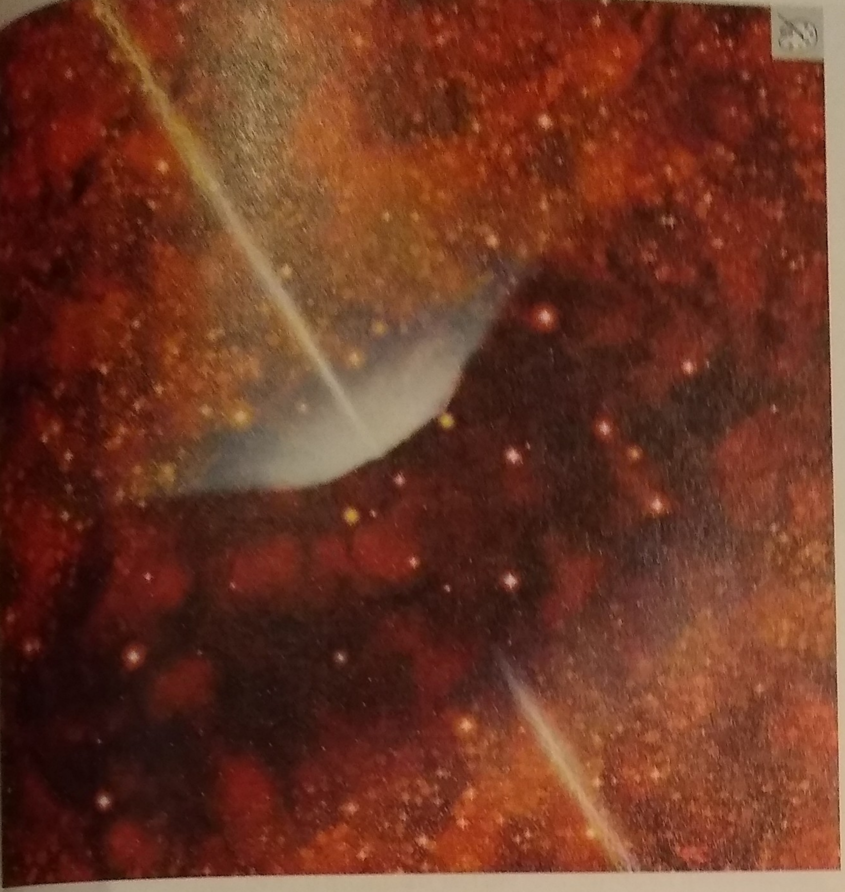


FIGURE 21.19 Artist's conception of the central few hundred light-years of a radio galaxy. The active galactic nucleus, obscured by a ring of dusty molecular clouds, lies at the point from which the jets emerge. If viewed along a direction closer to the jet axis, the active nucleus would not be obscured and it would therefore look more like a quasar.

Explaining the extreme luminosities of quasars was the main motivation for the supermassive black hole model. Matter falling into a black hole can generate awesome amounts of energy. During its fall to the event horizon of a black hole, as much as 10–40% of the mass-energy ($E = mc^2$) of a chunk of matter can be converted into thermal energy and ultimately to radiation. (The precise value for a particular black hole depends on its rotation rate: Faster rotation allows more energy to be released.) Accretion by black holes can therefore produce light far more efficiently than nuclear fusion, which converts less than 1% of mass-energy into photons. Remember that the light is coming not from the black hole itself but rather from the hot gas in the accretion disk that surrounds it.

FIGURE 21.20 Artist's conception of an accretion disk surrounding a supermassive black hole. This picture represents only the very center of an object like that shown in Figure 21.19.

The environment surrounding a supermassive black hole explains why active galactic nuclei emit light across such a broad wavelength range. Hot gas in and above the accretion disk produces enormous amounts of ultraviolet and X-ray photons. This radiation ionizes surrounding interstella gas, creating ionization nebulae that emit visible light. (The emission lines produced by these nebulae are the same one Maarten Schmidt used to measure the first quasar redshifts. Dust grains in the molecular clouds that encircle the active galactic nucleus (see Figure 21.19) absorb high-energy ligh and re-emit it as infrared light. Finally, the fast-movin electrons that we sometimes see jetting from these nuclei a nearly the speed of light can produce the radio emission fron active galactic nuclei.

The powerful jets emerging from active galactic nucle are more difficult to explain, but there is plenty of energ available for flinging material outward at nearly the spee of light. One plausible model for jet production relies o the twisted magnetic fields thought to accompany accretio disks around black holes, which are quite similar to the disk around protostars but orbit much faster. As an accretion dis spins, it pulls the magnetic field lines that thread it around i circles. Charged particles fly outward along the field lines lik beads on a twirling string, forming a jet that shoots out int space (**FIGURE 21.21**).

On the whole, the supermassive black hole model seem to explain the major observed features of quasars and oth active galactic nuclei. However, several important mysteri remain unsolved. For example, we do not yet know wl quasars eventually run out of gas to accrete and stop shining

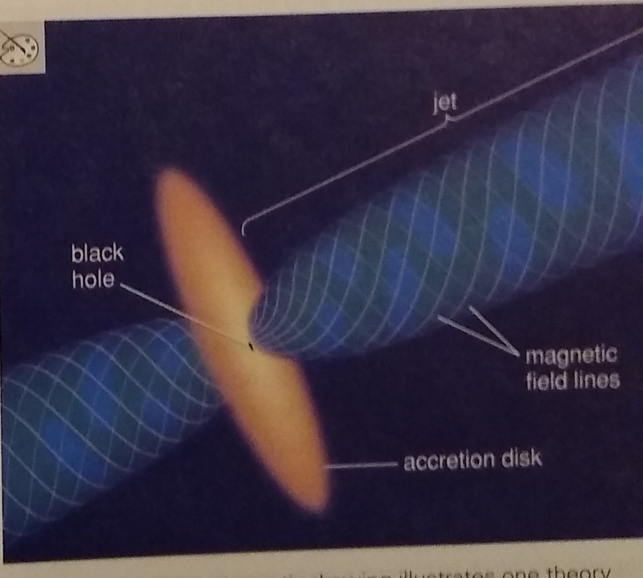


FIGURE 21.21 This schematic drawing illustrates one theory that might explain how supermassive black holes create jets. The theory relies on the magnetic field lines thought to thread the accretion disk surrounding a black hole. As the accretion dis spins, it twists the magnetic field lines. Charged particles at the accretion disk's surface can then fly outward along the twisted magnetic field lines.

brightly. We also do not know how those black holes formed in the first place. Nevertheless, the hypothesis that gigantic black holes are responsible for quasars, nearby active galactic nuclei, and radio galaxies has so far withstood the tests of thousands of observations.

Do supermassive black holes really exist?

The idea that such monster black holes really do exist is a difficult one to prove. Black holes themselves do not emit any light, so we need to infer their existence from the ways in which they alter their surroundings. In the vicinity of a black hole, matter should be orbiting at high speed around something invisible. We have already examined the evidence for a black hole at the center of our Milky Way [**Section 19.4**], but what about other galaxies?

Hunting for Supermassive Black Holes Detailed observations of matter orbiting at the centers of nearby galaxies suggest that supermassive black holes are quite common. In fact, it is possible that *all* galaxies contain supermassive black holes at their centers. One prominent example is the relatively nearby galaxy M87, which features a bright, active galactic nucleus and a jet that emits both radio and visible light (see Figure 21.13). It was therefore already a prime black hole suspect when astronomers pointed the Hubble Space Telescope at its core (FIGURE 21.22). The spectra they gathered showed blueshifted emission lines on one side of the nucleus and redshifted emission lines on the other. This pattern of Doppler shifts is the characteristic signature of orbiting gas: On one side of the orbit the gas is coming toward us and hence is blueshifted, while on the other side it is moving away from us and is redshifted. The magnitude of these Doppler shifts shows that gas located up to 60 light-years from the center is orbiting something invisible at a speed of hundreds of kilometers per second. This high-speed orbital motion indicates that the central object has a mass some 2–3 billion times that of our Sun.

Observations of NGC 4258, another galaxy with a visible jet, have delivered even more persuasive evidence. A ring of molecular clouds orbits the nucleus of this galaxy in a circle less than 1 light-year in radius. We can pinpoint these clouds because they amplify the microwave emission lines of water molecules, generating beams of microwaves very similar to laser beams. (The word *laser* stands for "light amplification by stimulated emission of radiation." These clouds contain water *masers*. The word *maser* stands for "microwave amplification by stimulated emission of radiation.") The Doppler shifts of these emission lines allow us to determine the orbits

MATHEMATICAL INSIGHT 21.1

Feeding a Black Hole

The fact that 10–40% of the mass-energy of matter falling into a black hole is radiated away as energy allows us to determine how much mass is accreting onto the black hole in an active galactic nucleus. For example, if 10% of the mass-energy is radiated away, then the amount of energy radiated by an infalling mass m is $E = \frac{1}{10}mc^2$. We simply solve for m to find the mass accreting onto the black hole:

$$\text{accreted mass} = m = 10 \times \frac{E}{c^2}$$

If the percentage of the mass converted to energy is larger, then a *smaller* amount of mass is needed. For example, if 20% of the mass becomes radiated energy, then only half as much mass is needed as under the assumption of 10%.

EXAMPLE: Consider a quasar with a luminosity of 10^{40} watts. How many solar masses of material must the central black hole consume each year if 10% of the mass-energy is radiated away? What if the quasar radiates away 25% of the mass-energy?

SOLUTION:

Step 1 Understand: The luminosity of 10^{40} watts means that the quasar radiates 10^{40} joules of energy each second (because 1 watt = 1 joule/s); the black hole must accrete enough mass to account for this energy. We can therefore use the above formula, remembering that 1 joule = 1 kg × m^2/s^2, to calculate how much mass the black hole accretes each second. Multiplying by the number of seconds in a year will tell us the annual accretion amount in kilograms, which we can convert to solar masses ($1M_{\text{Sun}} = 2.0 \times 10^{30}$ kg). The formula assumes that only 10% of the mass-energy is radiated away; if 25% were radiated away, then the amount of mass needed to explain the radiation would be only 10/25 = 0.4 times as much.

Step 2 Solve: We use the formula found above with the energy $E = 10^{40}\ \text{kg} \times \text{m}^2/\text{s}^2$ and the speed of light $c = 3 \times 10^8$ m/s:

$$m = 10 \times \frac{E}{c^2} = 10 \times \frac{10^{40}\ \dfrac{\text{kg} \times \text{m}^2}{\text{s}^2}}{\left(3 \times 10^8\ \dfrac{\text{m}}{\text{s}}\right)^2} = 1.1 \times 10^{24}\ \text{kg}$$

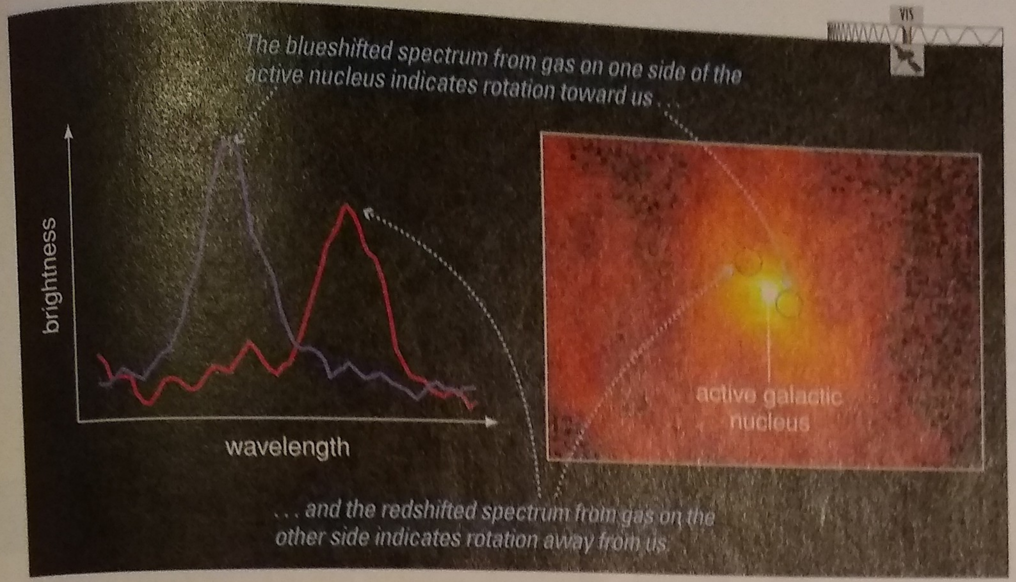
This is the mass accreted each second, so we find the annual accretion rate by multiplying by the number of seconds in 1 year:

$$1.1 \times 10^{24}\ \frac{\text{kg}}{\text{s}} \times 60\ \frac{\text{s}}{\text{min}} \times 60\ \frac{\text{min}}{\text{hr}} \times 24\ \frac{\text{hr}}{\text{day}} \times 365\ \frac{\text{day}}{\text{yr}}$$
$$= 3.5 \times 10^{31}\ \frac{\text{kg}}{\text{yr}}$$

We now convert from kilograms to solar masses:

$$\frac{3.5 \times 10^{31}\ \text{kg}/\text{yr}}{2.0 \times 10^{30}\ \text{kg}/M_{\text{Sun}}} \approx 17 M_{\text{Sun}}/\text{yr}$$

Step 3 Explain: To account for the quasar's luminosity, its central supermassive black hole must accrete the equivalent of about 17 Suns per year if it converts 10% of the accreted mass into energy that it radiates away. If it radiates away 25% of the mass-energy, then it must accrete about 0.4 × 17 ≈ 7 solar masses of material each year.



The blueshifted spectrum from gas on one side of the active nucleus indicates rotation toward us . . .

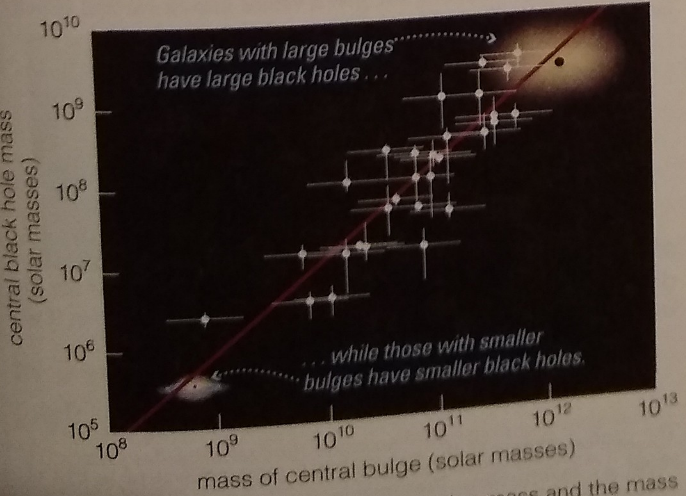
. . . and the redshifted spectrum from gas on the other side indicates rotation away from us.

FIGURE 21.22 This Hubble Space Telescope photo shows gas near the center of the galaxy M87, and the graph shows Doppler shifts of spectra from gas 60 light-years from the center on opposite sides (the circled regions in the photo). The Doppler shifts tell us that gas is orbiting the galactic center, and precise measurements tell us that the orbital speed is about 800 km/s. From the orbital speed and Newton's laws, we find that the central object must have a mass 2–3 billion times that of the Sun.

of the clouds very precisely. Their orbital motion tells us that the clouds are circling a single, invisible object with a mass of 36 million solar masses.

As the search for black holes in active galactic nuclei progresses, we are continuing to find examples like these. In each case, a supermassive black hole seems to be the only explanation for the enormous orbital speeds. We may never be 100% certain that these objects are indeed giant black holes. The best we can do is rule out all other possibilities, and a supermassive black hole is the only thing we know of that could be so massive while remaining unseen.

Black Holes and Galaxy Formation Evidence for supermassive black holes is also found in galaxies whose centers are not currently active, and the masses of those black holes follow a very interesting pattern: The mass of the black hole at the center of a galaxy appears to be closely related to the properties of the galaxy's spheroidal component. Detailed studies of the orbital speeds of stars and gas clouds in the centers of nearby galaxies show that the mass of the central black hole is typically about $\frac{1}{500}$ of the mass of the galaxy's bulge (FIGURE 21.23). Because this relationship holds for galaxies with a wide range of properties, from small spiral galaxies with a bulge mass of less than $10^8 M_{\text{Sun}}$ to giant elliptical galaxies whose spheroidal component exceeds $10^{11} M_{\text{Sun}}$, we conclude that the growth of a central black hole must be closely linked with the process of galaxy formation.



Galaxies with large bulges have large black holes . . .

. . . while those with smaller bulges have smaller black holes.

FIGURE 21.23 The relationship between bulge mass and the mass of a supermassive black hole.

Astronomers have long suspected that galaxy evolution goes hand in hand with the formation of supermassive black holes because quasars were so much more common early in time, when galaxies were growing rapidly. Unfortunately, we do not yet know how that process works. Some scientists have suggested that the black holes formed first out of gas at the centers of protogalactic clouds and that their energy output regulated the growth of the galaxy around them. Other scientists have suggested that clusters of neutron stars resulting from extremely dense starbursts at the centers of young galaxies might have somehow coalesced to form an enormous black hole, but these speculations are still unverified. The origins of supermassive black holes and their connection to galaxy evolution therefore remain mysterious.

How do quasars let us study gas between the galaxies?

The most mysterious part of galaxy evolution is the part we've not yet observed: the formation and development of protogalactic clouds. In recent years, the study of quasars has begun to shed light on this very early stage of galaxy evolution. The most distant quasars inhabit the outskirts of our observable universe. Photons from some of these quasars began journeying to Earth when the universe was less than 1 billion years old. Along the way, these photons have passed through numerous intergalactic hydrogen clouds. The vast majority of these clouds are too diffuse and wispy ever to become galaxies, but a few have as much hydrogen as the disk of the Milky Way. The thickest of these clouds may well be protogalactic clouds in the process of becoming galaxies.

Quasar spectra therefore contain valuable information about the properties of hydrogen clouds in the early universe. Because atoms tend to absorb light at very specific wavelengths, every time a light beam from a quasar passes through

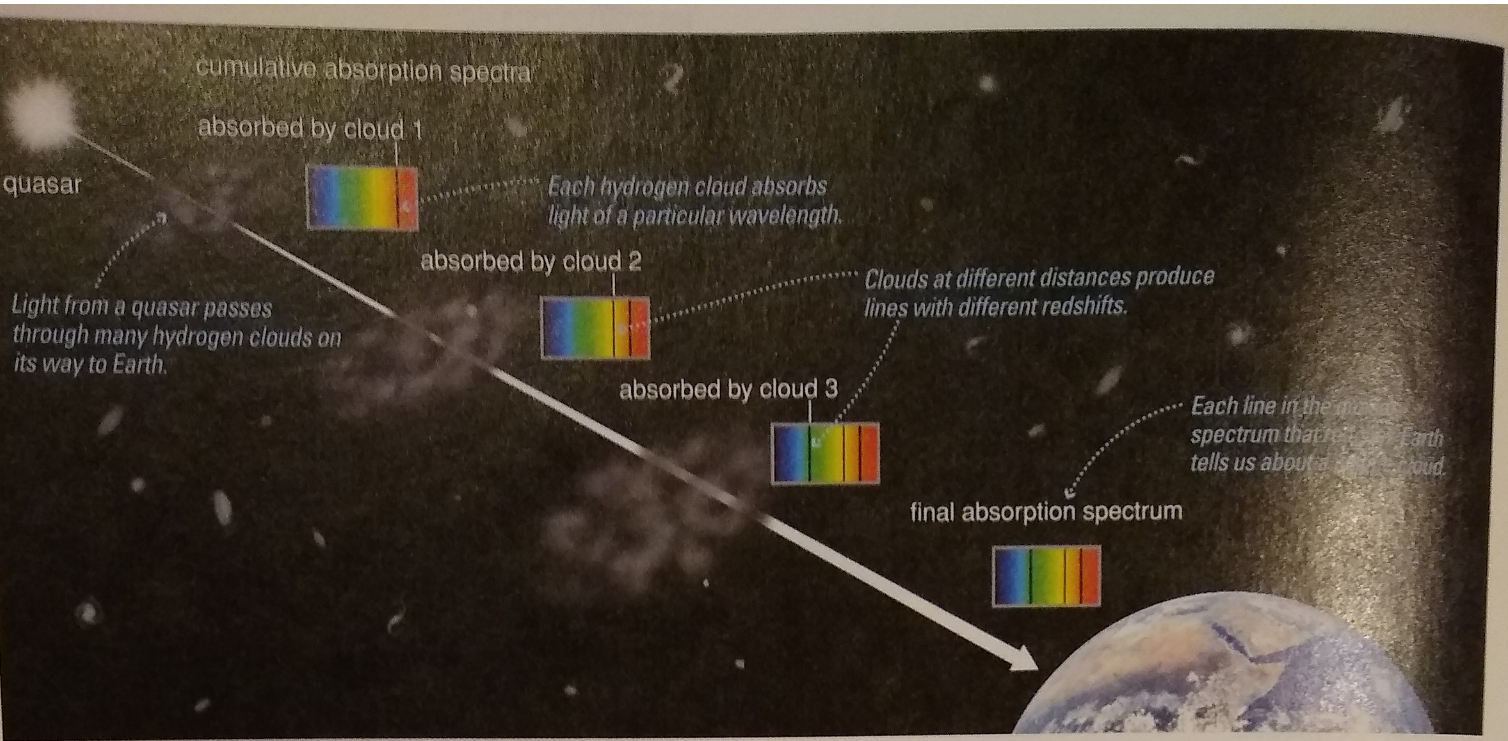


FIGURE 21.24 **interactive figure** This schematic illustration shows how interstellar hydrogen clouds leave their mark on the spectra of quasars. Each line in the quasar spectrum tells us about a unique hydrogen cloud between the quasar and Earth. As we study progressively redder lines, we learn about clouds in progressively earlier stages of the universe's development.

an intergalactic or protogalactic cloud, some of the atoms in the cloud absorb photons from the beam, creating an absorption line (**FIGURE 21.24**). Studies of these absorption lines in quasar spectra can tell us what happened in protogalactic clouds during the epoch of galaxy formation and provide clues about how galaxies evolve.

We are only beginning to learn how to read the clues that hydrogen absorption lines have etched into the spectra of quasars, but the evidence gathered so far supports our general picture of spiral galaxy evolution. The most prominent hydrogen absorption lines, thought to be associated with newly forming galaxies, are typically produced by the most distant clouds, indicating that the youngest galaxies are made mostly of gas. In fact, they contain about the same amount of mass in the form of hydrogen gas as older galaxies contain in the form of stars. The hydrogen lines from nearer clouds,

MATHEMATICAL INSIGHT 21.2

Weighing Supermassive Black Holes

We weigh supermassive black holes the same way we weigh almost everything else in the universe: by measuring the velocity v and orbital radius r of the matter circling the central black hole and then applying the orbital velocity law (see Mathematical Insight 19.1) to find the mass M_r within a distance r of the galactic center:

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

EXAMPLE: Doppler shifts show that ionized gas in the nucleus of the active galaxy M87 orbits at a speed of about 800 km/s at a radius of 60 light-years (5.6×10^{17} meters). Calculate the amount of mass that lies within 60 light-years of the galactic center.

SOLUTION:

Step 1 Understand: We are given both the orbital radius (r) and the orbital velocity (v) of gas clouds orbiting the center of the galaxy, so we can apply the orbital velocity law to determine the mass that lies within the distance r of the galactic center. For the units to work out properly, we use the orbital radius as given in meters and convert the orbital velocity to meters per second (800 km/s = 800,000 m/s, or 8.0×10^5 m/s).

Step 2 Solve: Substituting the given values into the orbital velocity law, we find

$$\begin{aligned} M_r &= \frac{r \times v^2}{G} \\ &= \frac{(5.6 \times 10^{17}\ \text{m}) \times (8.0 \times 10^5\ \text{m/s})^2}{6.67 \times 10^{-11}\ \text{m}^3/(\text{kg} \times \text{s}^2)} \\ &= 5.4 \times 10^{39}\ \text{kg} \end{aligned}$$

Step 3 Explain: The mass that resides within the orbits of the gas clouds is about 5.4×10^{39} kg. This mass is easier to interpret if we convert it to solar masses:

$$M_r = 5.4 \times 10^{39}\ \text{kg} \times \left(\frac{1 M_{\text{Sun}}}{2.0 \times 10^{30}\ \text{kg}}\right) = 2.7 \times 10^9 M_{\text{Sun}}$$

The central region of the galaxy has a mass equivalent to that of about 2.7 billion Suns. Presumably, nearly all this mass is in the central black hole.

which arise in more mature galaxies, are not nearly as strong. Presumably, a greater fraction of the gas in these galaxies has already collected into stars.

Absorption lines from elements other than hydrogen also support this picture. The lines from these heavy elements are more prominent in mature galaxies than in the youngest galaxies, implying that mature galaxies have experienced more supernovae, which have added heavy elements to their interstellar gas. This overall pattern of gradual heavy-element enrichment accompanied by the gradual diminishing of interstellar hydrogen agrees well with what we know about the Milky Way. All across the universe, stars in the gaseous disks of galaxies appear to have been forming steadily for over 10 billion years.

With every new study of a quasar spectrum, we learn more about the galaxies and intergalactic clouds that have left their mark on the light we observe from quasars. Perhaps someday soon, these observations will help us fit together all the pieces of the galaxy evolution puzzle, and we at last will understand the whole glorious history of galaxy evolution in our universe. Until that time, we will keep peering deep into space and back into time, searching for the clues that will unlock the mysteries of cosmic evolution.

The Big Picture

Putting Chapter 21 into Context

We have not yet solved the whole puzzle of galaxy evolution, but in this chapter we have described some of its crucial pieces. As you look back, keep sight of these "big picture" ideas:

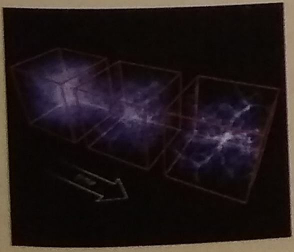
- We can study galaxy evolution by looking back through time: At great distances we see galaxies as they were when the universe was young, and nearby we see mature galaxies as they exist today. These observations, along with theoretical modeling, are helping us understand the lives of galaxies.
- Galaxies probably all began as systems of protogalactic clouds, but they do not always evolve peacefully. Some galaxies suffer gargantuan collisions with their neighbors, often with dramatic results.
- The tremendous energy outputs of quasars and other active galactic nuclei, including those of radio galaxies, are probably powered by gas accreting onto supermassive black holes. The centers of many present-day galaxies must still contain the supermassive black holes that once enabled them to shine as quasars.

SUMMARY OF KEY CONCEPTS

21.1 LOOKING BACK THROUGH TIME

- **How do we observe the life histories of galaxies?** Today's telescopes enable us to observe galaxies of many different ages because they are powerful enough to detect light from objects with lookback times almost as large as the age of the universe. We can therefore assemble "family albums" of galaxies at different distances and lookback times.

- **How do we study galaxy formation?** The most successful models of galaxy formation assume that galaxies formed as gravity pulled together regions of the universe that were ever so slightly denser than their surroundings. Gas collected in protogalactic clouds, and stars began to form as the gas cooled.



21.2 THE LIVES OF GALAXIES

- **Why do galaxies differ?** Differences between present-day galaxies probably arise both from conditions in their protogalactic cloud systems and from collisions with other galaxies. Slowly rotating or high-density systems of protogalactic clouds may form elliptical rather than spiral galaxies. Ellipticals may also form through the collision and merger of two spiral galaxies.
- **What are starbursts?** A **starburst galaxy** is a galaxy that is forming new stars at a very high rate—sometimes more than 100 times the star formation rate of the Milky Way. This high rate of star formation can lead to a supernova-driven **galactic wind.** Many starbursts apparently result from collisions between galaxies. Some starbursts may also occur as a result of close encounters with other galaxies rather than from direct collisions.

21.3 QUASARS AND OTHER ACTIVE GALACTIC NUCLEI

- **How are quasars powered?** Some galaxies have unusually bright centers known as **active galactic nuclei**; the most luminous of these are known as **quasars.** Quasars are generally found at very great distances, telling us that they were much more common early in the history of the universe. Quasars and other active galactic nuclei are thought to be powered by **supermassive black holes.** As matter falls into a supermassive black hole through an accretion disk, its gravitational potential energy is efficiently transformed into thermal energy and then into light.