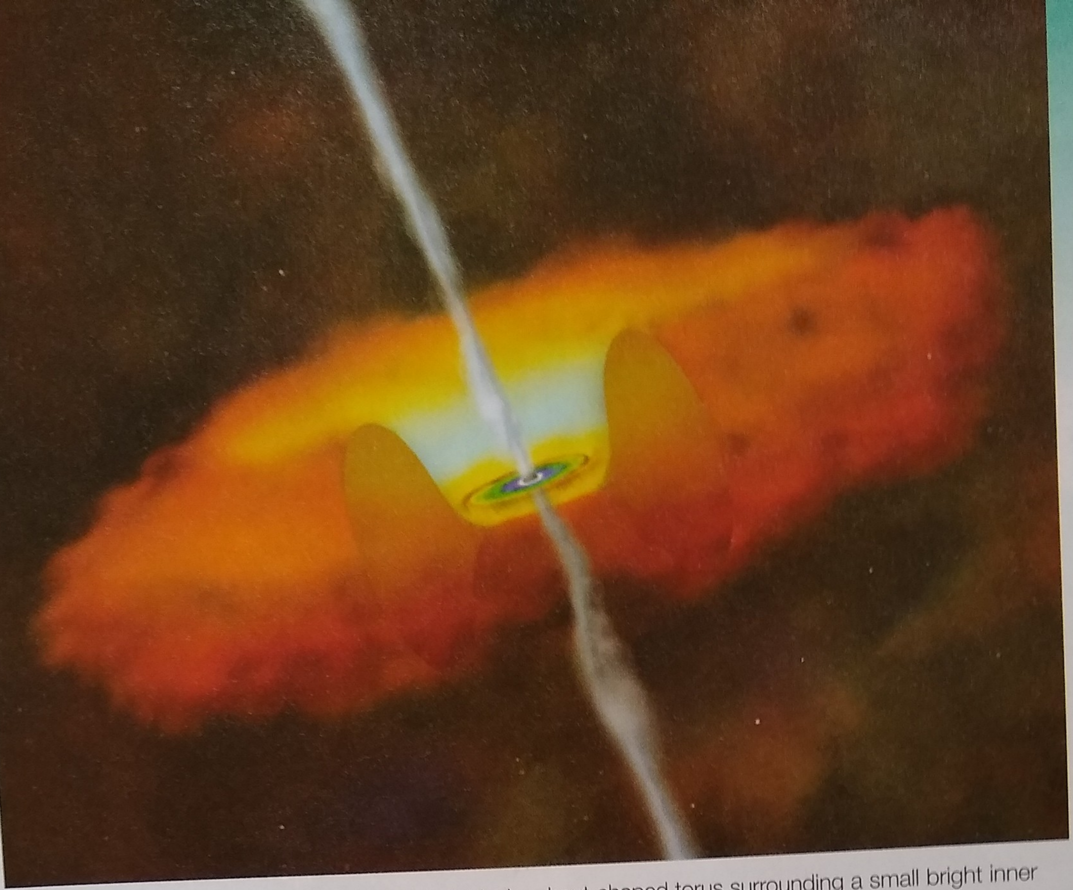
CHAPTER

24



This artist's conception of a quasar shows a thick doughnut-shaped torus surrounding a small bright inner region of hot swirling gas. The inner region is about the size of our solar system and is called an accretion disk. At the very center is a supermassive black hole that steadily consumes, or accretes, the surrounding gas. As illustrated here, some quasars have strong jets beaming away perpendicularly to the disk of swirling matter. While the outer torus can sometimes block much of the light emitted by the interior, when the interior light is visible, it can be a hundred thousand times as bright as our Milky Way Galaxy! (NASA/CXC/M.Weiss)

Quasars and Active Galaxies

LEARNING GOALS

By reading the sections of this chapter, you will learn

24-1 The distinctive features of quasars

24-2 The role of supermassive black holes in powering active galactic nuclei (AGN)

24-3 How quasars can form accretion disks and jets

24-4 That active galactic nuclei can look very different depending on their orientation

24-5 The fate of active galactic nuclei and their potential to occasionally flare up

An ordinary star emits radiation primarily at ultraviolet, visible, and infrared wavelengths, in varying proportions that are governed by the star's surface temperature. Composed of many stars, ordinary galaxies, too, emit most strongly in these wavelength regions. But the object illustrated here, called a quasar, is outrageously different: It emits strongly over an immense range of wavelengths from radio to X-ray.

The name quasar refers to one of the most fantastic types of objects in all of astronomy. At a quasar's core is a supermassive black hole that can be a *billion* times more massive than our Sun! Hot gas around this black hole can give off a tremendous amount of visible light—enough to shine with a luminosity *ten thousand* times more than a typical galaxy.

As in this illustration, some quasars even have strong jets. Unlike young stars that form smaller and slower-speed jets, matter in quasar jets travels near the speed of light and can shoot well beyond the galaxy that hosts the quasar. Galaxies that hold a quasar—always at the galaxy's center—are called *active galaxies.* Untangling the mysterious properties of quasars has been in process for more than half a century and is still a major topic of research today. Physicist George Gamow captured the intriguing nature of quasars in his 1964 revised lullaby:

Twinkle, twinkle quasi-star
Biggest puzzle from afar
How unlike the other ones
Brighter than a billion suns.
Twinkle, twinkle quasi-star
How I wonder what you are.

24-1 Quasars are the ultraluminous centers of distant galaxies

The discovery of quasars begins in the Illinois backyard of Grote Reber, a radio engineer who built the first true radio telescope in 1936. One of the objects he discovered is called Cygnus A; a modern radio and optical image of this quasar is shown in Figure 24-1. The object's thin jets shoot matter well beyond its host galaxy; to appreciate the scale, consider that about four Milky Way galaxies could fit between the ends of the two lobes in Cygnus A.

Examining the spectra of quasars revealed that they are immensely distant

In a visible-wavelength image, a distant quasar often appears as a point source of light, like a star, because the host galaxy containing the quasar is so far away that the galaxy's light is not easily observed (Figure 24-2). Along with intense radio emission, these properties led to the name "quasar," which means *quasi-stellar radio source.*

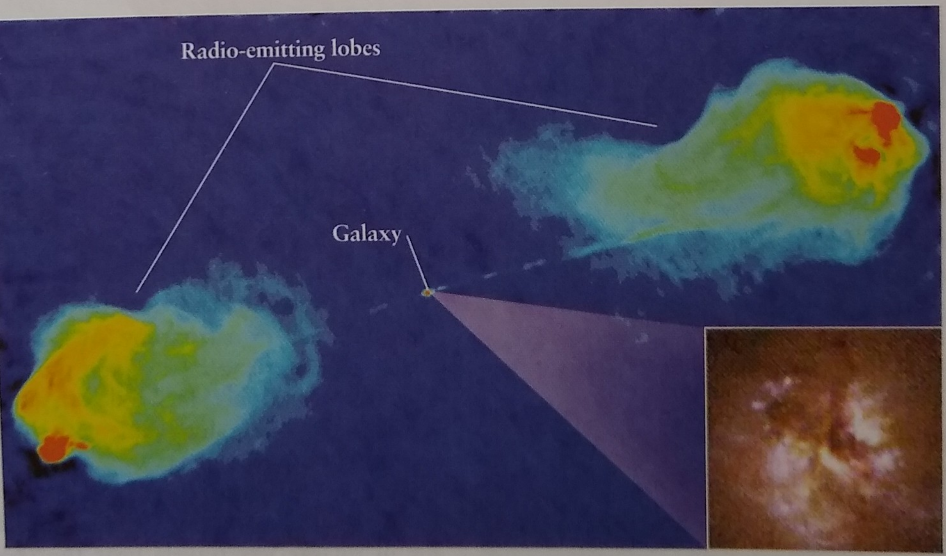
While the visible light from a quasar might appear pointlike, the way a star does, its spectrum tells a very different story. Stars, and the galaxies they make up, show absorption lines in t spectra. Quasars, on the other hand, show strong *emission* lin

Clues from Emission Lines

Although quasars were clearly oddballs, many astronom thought they were just strange stars in our own Galaxy. A br through occurred in 1963, when Maarten Schmidt at Cal took another look at the emission lines of the quasar 3C (Figure 24-3). Emission lines are caused by excited atoms, w emit radiation at specific wavelengths unique to each atom Figure 6-21). However, the lines of quasar 3C 273 did not m the known emission line wavelengths of hydrogen (or any c known atoms or molecules), so astronomers could not ide what quasars were made of.

Schmidt realized that four of 3C 273's brightest emission are positioned relative to one another in precisely the same as four common emission lines of hydrogen (these are the Ba lines; see Figure 5-24). However, these emission lines from 3C were all shifted to *much longer wavelengths* than had ever been in the Balmer lines before. Were these lines really from hydr but Doppler-shifted from an object receding away at great sp Schmidt determined that 3C 273 has a redshift of $z = 0.158$, c sponding to a recessional velocity equal to 16% of the speed of (44,000 km/s). No star could be moving this fast and remain w our Galaxy for very long. Hence, Schmidt concluded that 3C could not be a nearby star, but must lie outside the Milky Wa

According to the Hubble law, the recessional veloci 3C 273 implies that its present distance from us is 2 b light-years; that is over 800 times farther away from us tha Andromeda Galaxy! To be detected at such distances, 3C



R I V U X G

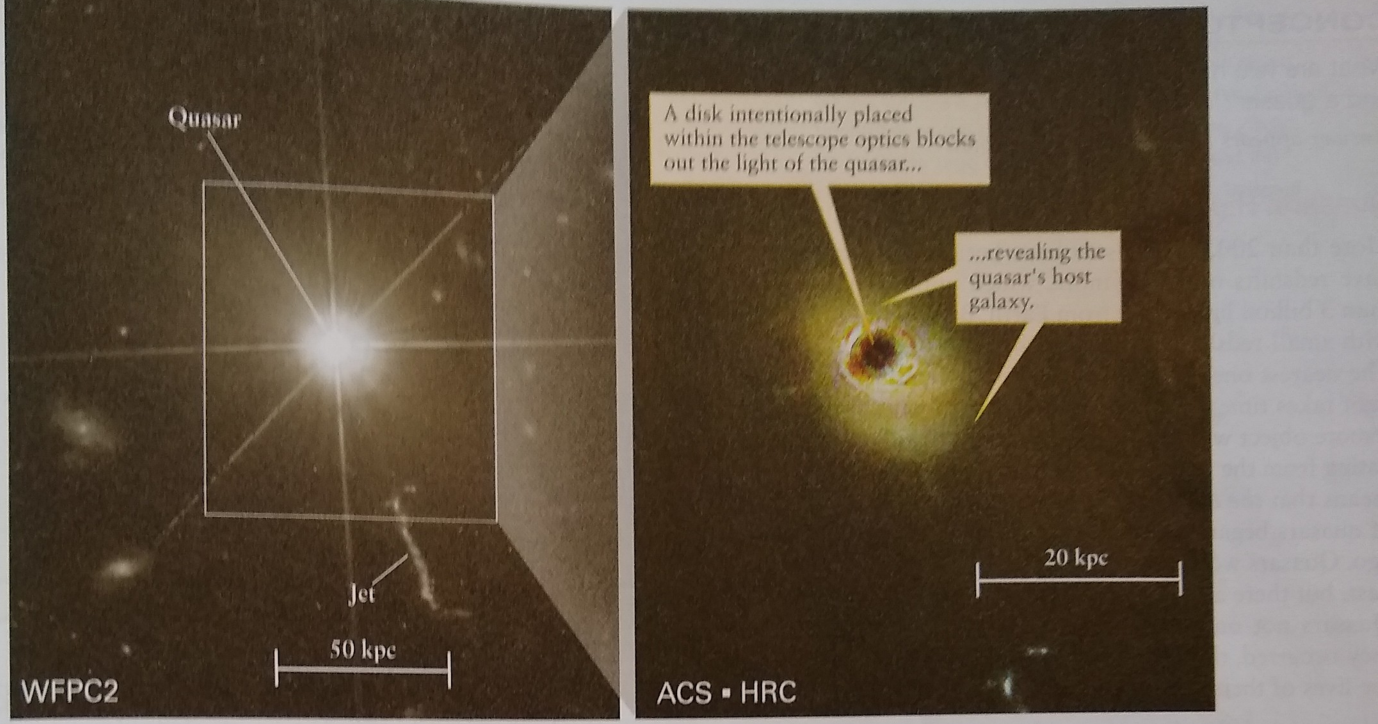
(a) Radio image of Cygnus A

R I V U X G

(b) Visible-light close-up of the central galaxy

FIGURE 24-1

Cygnus A **(a)** This false-color radio image from the Very Large Array shows that most of the emission from Cygnus A comes from luminous radio lobes located on either side of a peculiar galaxy. (Red indicates the strongest radio emission, while blue indicates the faintest). Each lobe extends about 230,000 ly) from the galaxy. **(b)** The galaxy at the heart of Cygnus A has a substantial redshift, so it must be extremely far from Earth (it is about 740 million ly). C the very brightest central region of the galaxy is visible here. To be so dista and yet be one of the brightest radio sources in the sky, Cygnus A must h enormous energy output. (a: NRAO/AUI; b: Hubble Space Telescope, cropped fr mosaic of three images by Bill Keel)



A disk intentionally placed within the telescope optics blocks out the light of the quasar...

...revealing the quasar's host galaxy.

FIGURE 24-2 R I **V** U X G
A Quasar and Its Host Galaxy (a) Appearing pointlike, a quasar can look like a star in images. In this HST image, the bright glare of a quasar named 3C 273 hides its fainter host galaxy. Quasar 3C 273 also has a jet seen in visible light, although quasar jets are usually seen at radio wavelengths. (b) Using a special technique, the quasar is blocked out to reveal the host galaxy. (NASA, A. Martel [JHU], the ACS Science Team, J. Bahcall [IAS] and ESA)

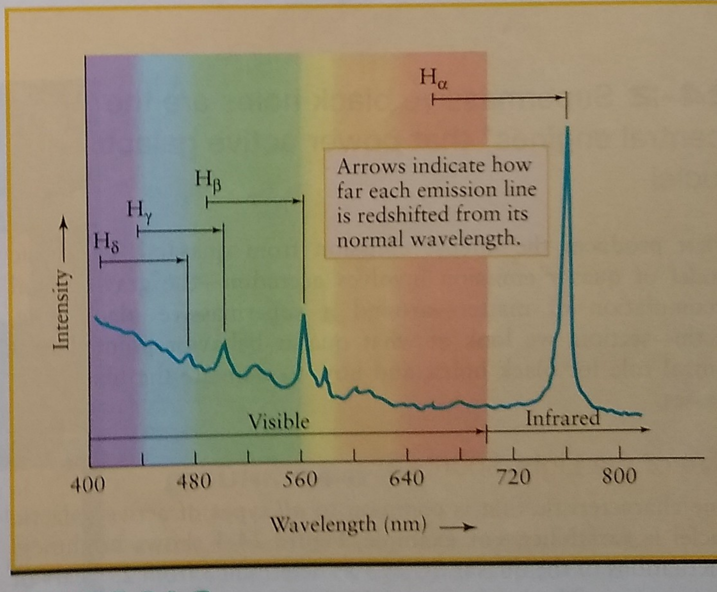
must be an extraordinarily powerful source of both visible light and radio emission.

A quasar's luminosity can be calculated from its apparent brightness and distance using the inverse-square law (see Section 17-2). For example, 3C 273 has a luminosity of about 10^{40} watts, which is equivalent to 2.5×10^{13} (25 trillion) Suns. (The Sun's luminosity is $L_\odot = 3.90 \times 10^{26}$ watts.) Generally, quasar luminosities range from about 10^{38} watts up to nearly 10^{42} watts. For comparison, a typical large galaxy, like our own Milky Way, shines with a luminosity of 10^{37} watts, which equals 2.5×10^{10} (25 billion) Suns. Thus, a bright quasar can be many thousands of times more luminous than our entire Milky Way Galaxy!

The most luminous quasars emit 100,000 times more radiation than the entire Milky Way Galaxy

Quasars are members of a larger class of objects called **active galactic nuclei**, or **AGN** (the singular form, active galactic nucleus, is also called an AGN). AGN include a range of similar objects that, technically speaking, are not all luminous enough to be called quasars. Nonetheless, all AGN are powered by hot gas accreting around a supermassive black hole, and astronomers often use the term quasar and AGN interchangeably. If the host galaxy that contains an AGN can be easily observed, the object is called an **active galaxy**. If the active galaxy emits strongly at radio wavelengths, as in the case of Cygnus A in Figure 24-1, the AGN is called a **radio galaxy**.

The rapid variability of active galactic nuclei tells us that they must be very small



Arrows indicate how far each emission line is redshifted from its normal wavelength.

FIGURE 24-3
The Spectrum of a Quasar The visible-light and infrared spectrum of quasar 3C 273 is dominated by four bright emission lines of hydrogen (see Section 5-8). The redshift is $z = 0.158$, so the wavelength of each line is 15.8% greater than for a sample of hydrogen on Earth. For example, the wavelength of H_β is shifted from 486 nm (a blue-green wavelength) to $1.158 \times (486\ \text{nm}) = 563$ nm (a yellow wavelength).

CONCEPTCHECK 24-1

What are two main differences between the spectra of a star and a quasar?

Answer appears at the end of the chapter.

Quasars: High Redshifts, Extreme Distances

More than 200,000 quasars have been discovered. Most quasars have redshifts of 0.3 or more, which implies that they are more than 3 billion light-years from Earth. Because there are no quasars with small redshifts, it follows that *there are no nearby quasars.* The nearest one is some 800 million ly from Earth. Furthermore, light takes time to travel across space, so when we observe a very remote object with a large redshift, we are seeing an image propagating from the remote past. Hence, the absence of nearby quasars means that *the era of quasars ended long ago.* Indeed, the number of quasars began to decline precipitously roughly 10 billion years ago. Quasars were a common feature of the universe in the distant past, but there are none in the present-day universe (Figure 24-4). Quasars not only occurred early in our universe, but whenever they occurred, their brief lifetimes were only about 1% as long as the lives of their host galaxies.

CONCEPTCHECK 24-2

From Figure 24-4, about how old was the universe when quasars were most abundant? What is the approximate redshift of objects from this time?

CONCEPTCHECK 24-3

Why can we say that any quasar observed from Earth today must have been very luminous when its light was emitted?

Answers appear at the end of the chapter.

24-2 Supermassive black holes are the "central engines" that power active galactic nuclei

What produces the intense emission from quasars? The basic model of quasar emission involves **accretion**—the gravitational accumulation of matter—around a supermassive black hole. In this section, we look at what quasar behavior pointed to a central role for black holes, and how to estimate the black hole masses.

Size of the Light Source

One characteristic that is common to *all* types of active galactic nuclei is variability. For example, Figure 24-5 shows brightness fluctuations of the quasar 3C 273 as determined from 29 years of observations. The brightness of 3C 273 increased by 60% from the beginning to the end of 1982, then declined to the starting value in just five months. Other AGN undergo even greater fluctuations in brightness (by a factor of 25 or more) that occur even more rapidly (X-ray observations reveal that some AGN vary in brightness over time intervals as short as 3 hours).

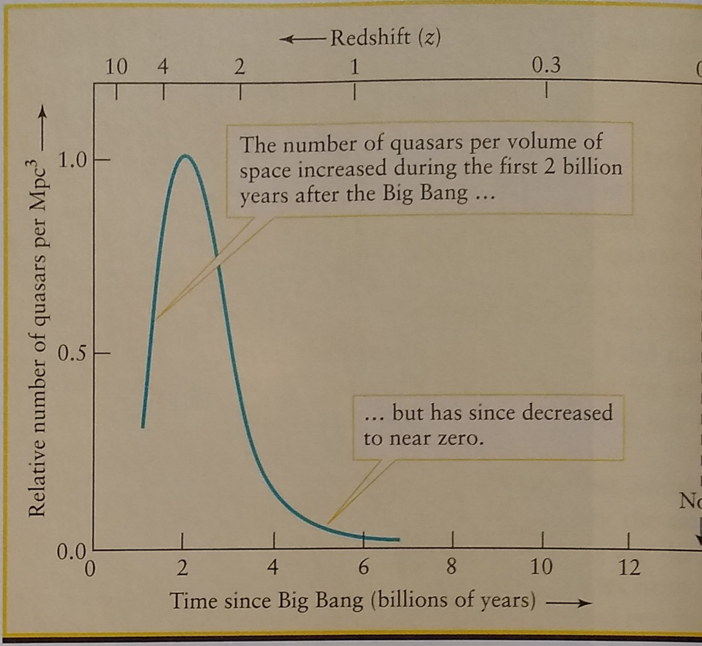


FIGURE 24-4

Quasars Are Extinct The greater the redshift of a quasar, the farthe
is from Earth and the farther back in time we are seeing it. By observin
number of quasars found at different redshifts, astronomers can calcula
how the density of quasars in the universe has changed over the histor
the universe. The peak of quasar activity occurred more than 10 billion
ago, and there is no significant quasar activity today. The history of qua
reminiscent of the history of the dinosaurs, which once populated the e
Earth but today are extinct. (Peter Shaver, European Southern Observatory)

The crucial aspect of these fluctuations in brightness is tha
allow astronomers to place fundamental limits on the max
size of a light source. This strict limit arises because *an objec
not vary in brightness faster than light can travel across that o*
For example, an object that is 1 light-year in diameter canno
significantly in brightness over a period of less than 1 year.

To understand this limitation, imagine an object that mea
1 light-year across, as in Figure 24-6. Suppose the entire
suddenly brightens, emitting a brief flash of light. Photons
that part of the object nearest Earth arrive at our telescopes
Photons from the middle of the object arrive at Earth 6 m
later. Finally, light from the far side of the object arrives a
after the first photons. Although the object emitted a sudden
of light, we observe only a gradual increase in brightness
lasts a full year. In other words, the flash is stretched out ov
interval equal to the difference in the light travel time betwee
nearest and farthest observable regions of the object.

The rapid flickering exhibited by active galactic nuclei m
that they emit their energy from a small volume—in some
less than half a light-day across (which is about the diamet
Neptune's orbit). Thus, from quasar variability, astronomers
covered that *a region about the size of our solar system can
more energy per second than a thousand galaxies!* More than
thing else, this size-constraint points to supermassive black h
as no other known object can power the release of so much en
from such a small volume.

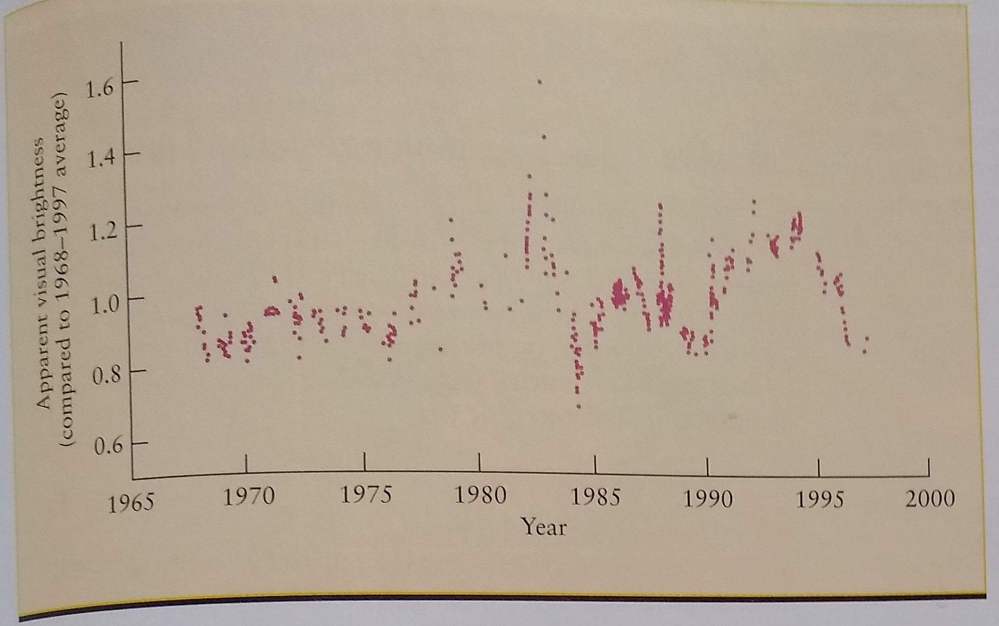


FIGURE 24-5

Brightness Variations of an AGN This graph shows variations over a 29-year period in the apparen brightness of the quasar 3C 273 (see Figure 24-2a, b). Note the large outburst in 1982–1983 and the somewhat smaller ones in 1988 and 1992. (Adapted from M. Türler, S. Paltani, and T. J.-L. Courvoisier)

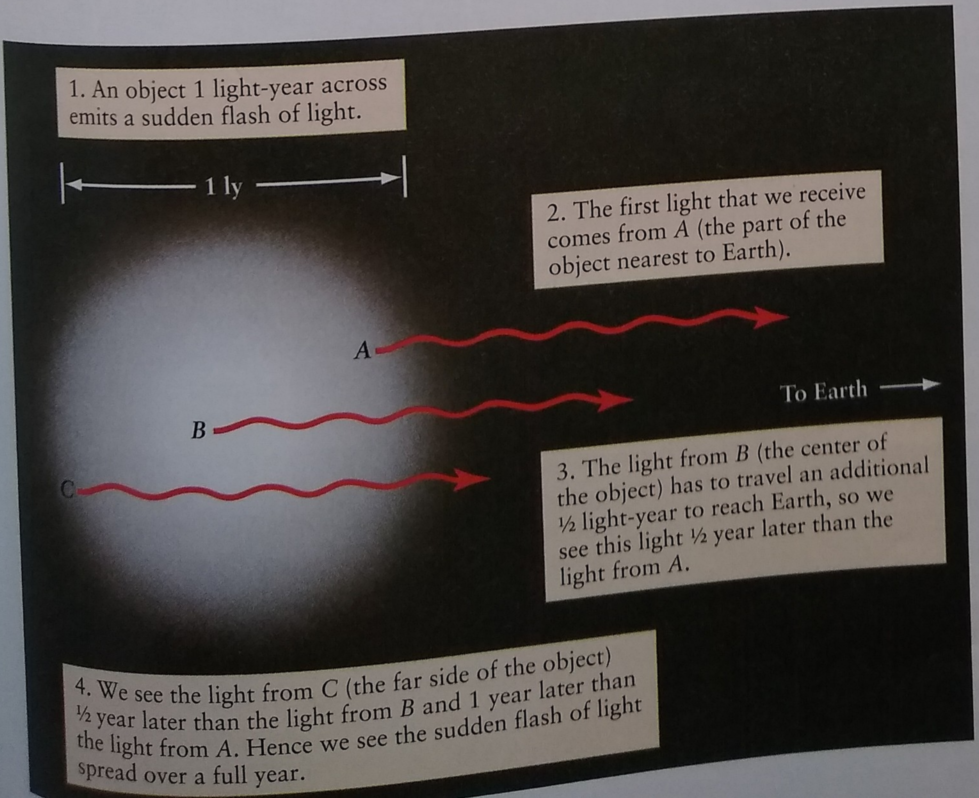
CAUTION! Quasars are intensely luminous, but their central black holes do not emit this light. Instead, the light is emitted by hot gas swirling around the black hole. The black holes are still considered the "central engines" of the quasar because it is the black hole's gravity that pulls in the surrounding gas and heats it up.

While the light-emitting region in a quasar might be about the size of our solar system, the black hole is smaller still. Just how big and massive are the black holes in quasars? Surprisingly, the size and mass of the black hole can be estimated from great distances where nothing is seen but the light from its hot accreting gas.

The Eddington Limit and Black Hole Sizes

There is a relationship between the size of a black hole luminosity emitted by the hot gas falling into it. Even if plenty of gas around to act as "fuel," there is a natural lim luminosity that can be radiated by accretion onto a compa like a black hole. This limit is called the **Eddington limit,** British astrophysicist Sir Arthur Eddington. The Eddingt applies to any object held together by its own gravity an to stars as well as quasars.

The accretion of fuel by a black hole is thought to be a and steady process, but let's imagine what might happen if



1. An object 1 light-year across emits a sudden flash of light.

2. The first light that we receive comes from *A* (the part of the object nearest to Earth).

3. The light from *B* (the center of the object) has to travel an additional ½ light-year to reach Earth, so we see this light ½ year later than the light from *A*.

4. We see the light from *C* (the far side of the object) ½ year later than the light from *B* and 1 year later than the light from *A*. Hence we see the sudden flash of light spread over a full year.

FIGURE 24-6

A Limit on the Speed of Variations in Brightness The rapidity with which the brightn of an object can vary significantly is limited by the time it takes light to travel across the object. If an object 1 light-year in size emits a sudden flash of light, the flash will be observed from Earth to last a full year. If the object is 2 light-years in size brightness variations will last at least 2 years as seen from Earth, and so on.

were to suddenly brighten. If the luminosity exceeds the Eddington limit, there is so much *radiation pressure*—the pressure produced by photons streaming outward from the infalling material—that the surrounding gas is pushed outward rather than falling inward onto the black hole. Without a source of gas to provide energy, the luminosity naturally decreases to below the Eddington limit, at which point gas can again fall inward. Thus, *the Eddington limit represents the balance between radiation pushing gas-fuel outward and gravity pulling the gas inward.* This limit allows us to calculate the minimum mass of the black hole in a quasar.

Numerically, the Eddington limit is

The Eddington limit

$$L_{\mathrm{Edd}} = 30{,}000 \left(\frac{M}{M_\odot}\right) L_\odot$$

L_{Edd} = maximum luminosity that can be radiated by accretion around a black hole

M = mass of the black hole

$M_\odot$ = mass of the Sun

$L_\odot$ = luminosity of the Sun

The tremendous luminosity of a quasar must be less than or equal to its Eddington limit (or it would blow away its accreting gas), so this limit must be very high indeed. Hence, the mass of the black hole must also be quite large. For example, consider the quasar 3C 273, which has a luminosity of about $3 \times 10^{13}\ L_\odot$. To calculate the minimum mass of a black hole that could continue to attract gas to power the quasar, assume that the quasar's luminosity equals the Eddington limit. Inserting $L_{\mathrm{Edd}} = 3 \times 10^{13}\ L_\odot$ into the above equation, we find that $M = 10^9\ M_\odot$. Therefore, if a black hole is responsible for the energy output of 3C 273, its mass must be greater than a billion Suns!

Astronomers have indeed found evidence for such **supermassive black holes** at the centers of many nearby normal galaxies (see Section 22-5), and these are thought to be the remnants of AGN. As we saw in Section 22-6, at the center of our own Milky Way Galaxy lies what is almost certainly a black hole of about 4.1×10^6 solar masses—supermassive in comparison to a star, but less than 1% the mass of the behemoth black hole at the center of 3C 273.

Most or all large galaxies have supermassive black holes at their centers

Unlike stellar-mass black holes, which require a supernova to produce them, supermassive black holes can be produced without extreme densities. Recall (Section 21-5) that matter with an average density no greater than water could form a 500 million $M_\odot$ black hole if this matter coalesced into a sphere with a radius about the Earth–Sun distance (1 AU). Some astronomers suspect that galaxy collisions produced massive black holes that accreted their way to even larger sizes, but the origin of supermassive black holes, and the AGN they powered, remains a mystery.

CONCEPTCHECK 24-4

Suppose a quasar's luminosity is initially right at the Eddington limit. What would happen if the quasar were somehow able to
temporarily become even brighter without a significant cha
in its mass?

Answer appears at the end of the chapter.

24-3 Quasar accretion disks and jets

Accretion—the capture and consumption of material—by a su
massive black hole is the most likely explanation of the imm
energy output of active galactic nuclei. The challenge to astrop
icists is to understand how that accretion takes place. A succe
model of the accretion process must also explain other prope
of active galactic nuclei, including their unusual spectra, var
light output, and energetic jets.

Accretion Disks around Supermassive Black Hole

In the leading model of this process, at the heart of an active galaxy is a supermassive black hole surrounded by an **accretion disk,** a solar system–sized disk of matter captured by the hole's gravity and spiraling into it. We saw in Section
18-5 that accretion disks are found around stars in the proce
formation. The accretion disks that astrophysicists envision ar
supermassive black holes are similar but far larger and far
dynamic. The *Cosmic Connections: Accretion Disks* figure de
the physics of such accretion disks.

The power source for acti
galaxies is gravitational
energy released by materi
falling toward a central bl
hole

Imagine a billion-solar-mass black hole sitting at the cent
a galaxy, surrounded by a rotating accretion disk. Accordir
Kepler's third law, the inner regions of this accretion disk w
orbit the hole more rapidly than would the outer parts. Thus
rapidly spinning inner regions would constantly rub agains
slower moving gases in the outer regions. This friction, aide
magnetic forces within the disk, would cause the gases to lose er
and spiral inward toward the black hole.

As the gases move inward within the accretion disk, the
compressed and heated to very high temperatures. This cause
accretion disk to glow, thus producing the brilliant luminosity
active galactic nucleus. The temperature of material in the accr
disk reaches 100,000 K or more, which emits thermal radi
primarily at UV and visible wavelengths. (By comparison, the
is around 5800 K and the hottest blue stars are around 50,000

In this model, the fundamental source of the energy outpu
an active galactic nucleus is *gravitational* energy converted into
released as, thermal radiation by infalling material in the accr
disk. We saw in Section 20-6 that gravitational energy is also
powers the immense light output of a core-collapse supernova.
difference between such a supernova and an active galactic nucle
that the infall of a supernova's outer layers is a one-time event,
gas in an AGN's accretion disk spirals inward continuously.

This model of accretion works well for smaller disks suc
those around neutron stars or stellar mass black holes. Howev
much as it is the favored model, detailed accretion disk calcula
for AGN are a poor fit to actual observations. Whether qu
derive their intense luminosity through accretion disks, a more
plicated accretion scenario, or some other process is still unkn
Until the emission mechanism for quasars is understood, it is l
to remain on the frontier of modern research.

Jets of Charged Particles

Because of the constant inward crowding of hot gas in the plane of the accretion disk, pressures climb rapidly near the center. These pressures expel matter at extremely high speeds. This ejected material escapes at right angles to the plane of the accretion disk and the material forms into two jets (Figure 24-7). However, the active galaxy M87 only shows a single jet. Similar to a flashlight beam, we can clearly see the jet pointed toward us, but the jet pointing away is not visible (Figure 24-8) For AGN, the matter in the jets travels at nearly the speed of light, and this leads to beamed emission that is only visible when pointed somewhat toward the observer.

Magnetic forces play a crucial role in steering these fast-moving particles. These forces arise because the hot gases in the accretion disk are ionized, forming a plasma, and the motions of this plasma generate a magnetic field (see Section 16-9). As the plasma in the disk rotates around the black hole, it pulls the magnetic field along with it. But because the disk rotates faster in its inner regions than at its outer rim, the magnetic field becomes severely twisted. This twisted field forms two helix shapes, one on either side of the plane of the disk.

Charged particles flowing outward from the accretion disk tend to follow these magnetic field lines. The result is that the outflowing beams of particles are focused into two jets oriented perpendicular to the plane of the accretion disk. The figure that opens this chapter is an artist's conception of the accretion disk and jets. The highly collimated jets shoot well beyond the host galaxy, and very diffuse gas in the space between galaxies spreads the jets into radio lobes, as in Figure 24-1. Jets are primarily observed at radio wavelengths but some jets can also be seen at visible wavelengths and even X-rays (Figure 24-9). It is not known if the charged particles in jets are composed of electrons and protons, or electrons and their antimatter partners, the positrons.

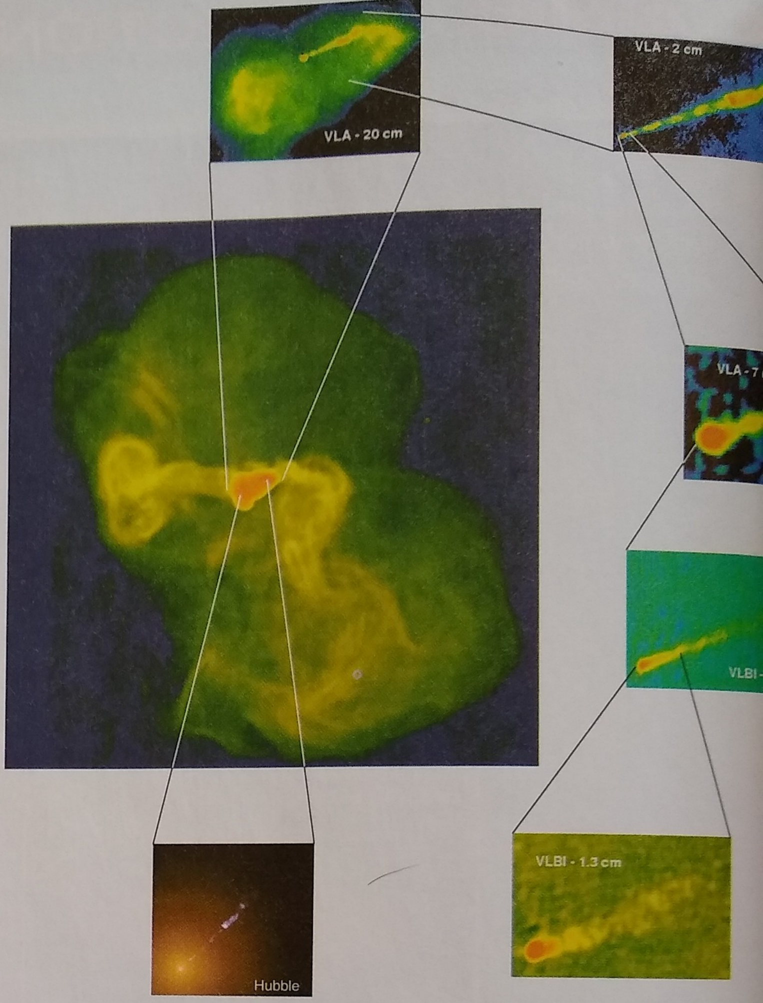


FIGURE 24-8 R I V U X G

Giant Elliptical Galaxy M87 M87 is located near the center of the sprawling, rich Virgo cluster, which is about 50 million ly from Earth. Embedded in this radio image of gas is the galaxy M87 from which the gas has been ejected (bottom inset). The bottom inset is a visible light image from the Hubble Space Telescope, and the rest are at radio wavelengths. As the images zoom into smaller scales, they reveal a variety of details about the structure of the jets of gas. M87's extraordinarily bright nucleus and the gas jets result from a 3-billion-$M_\odot$ black hole, whose gravity causes huge amounts of gas and an enormous number of stars to crowd around it. (NASA and the Hubble Heritage Team [STScI/AURA]; Frazer Owen [NRAO], John Biretta [STScI] and colleagues)

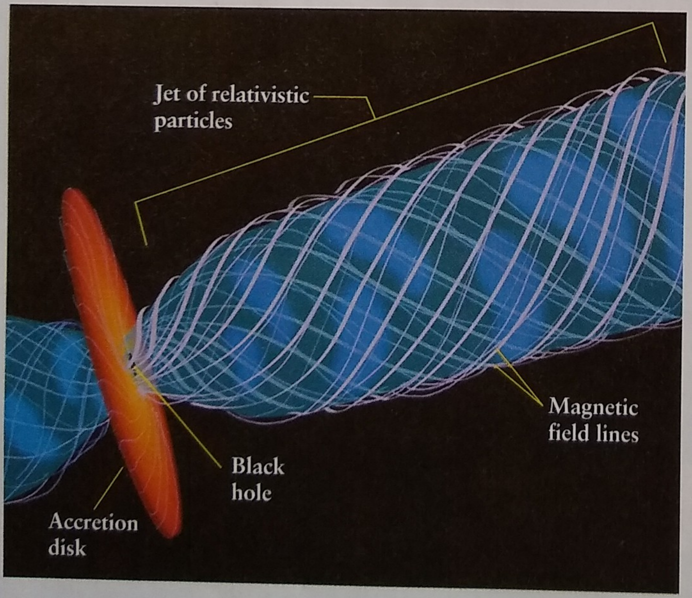


FIGURE 24-7

Jets from a Supermassive Black Hole The rotation of the accretion disk surrounding a supermassive black hole twists the disk's magnetic field lines into a helix. The field then channels the flow of subatomic particles pouring out of the disk. Over a distance less than a light-year, this channeling changes a broad flow into a pair of tightly focused jets, one on each side of the disk. Figure 18-16 shows a similar process that takes place on a much smaller scale in protostars. (NASA and Ann Feild, Space Telescope Science Institute)

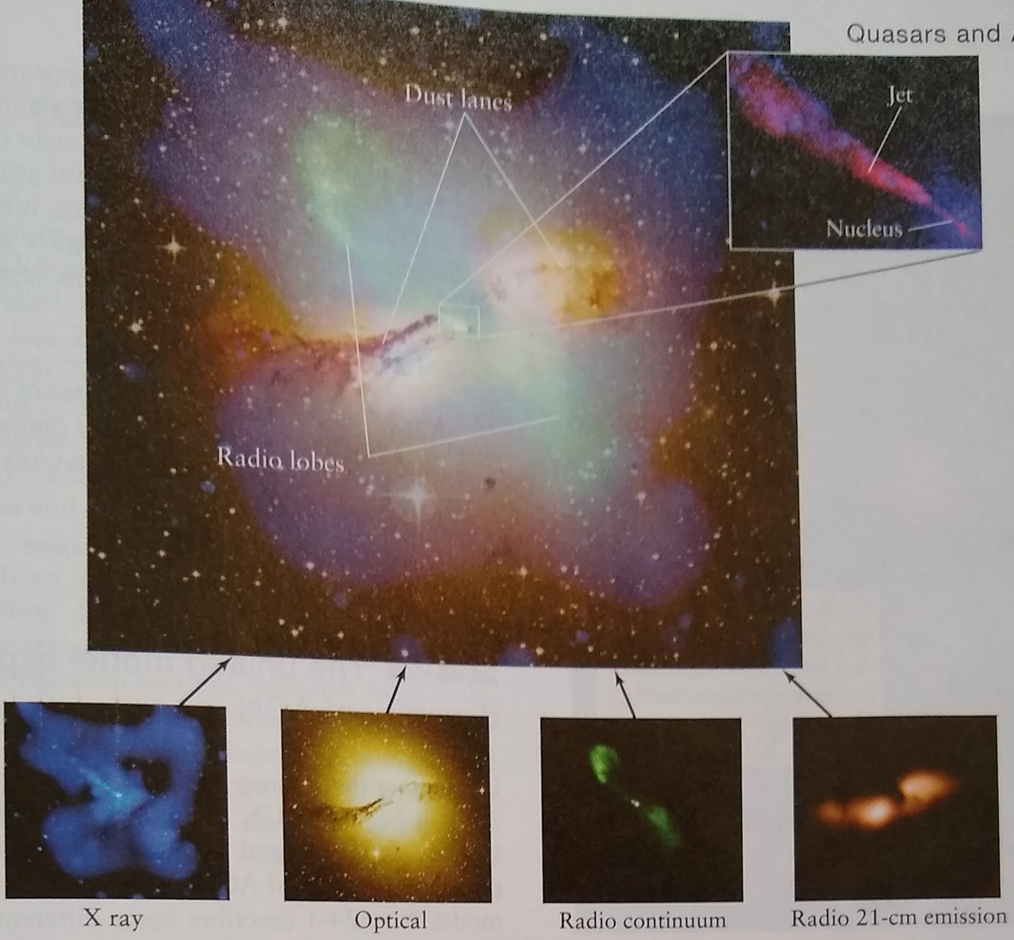
CONCEPTCHECK 24-5

In the accretion disk model, what happens when an inner blob of gas passes an outer blob of gas during accretion (see Cosmic Connections: Accretion Disks)? How is light produced in an accretion disk?

Answer appears at the end of the chapter.

The Strange Case of Superluminal Motion

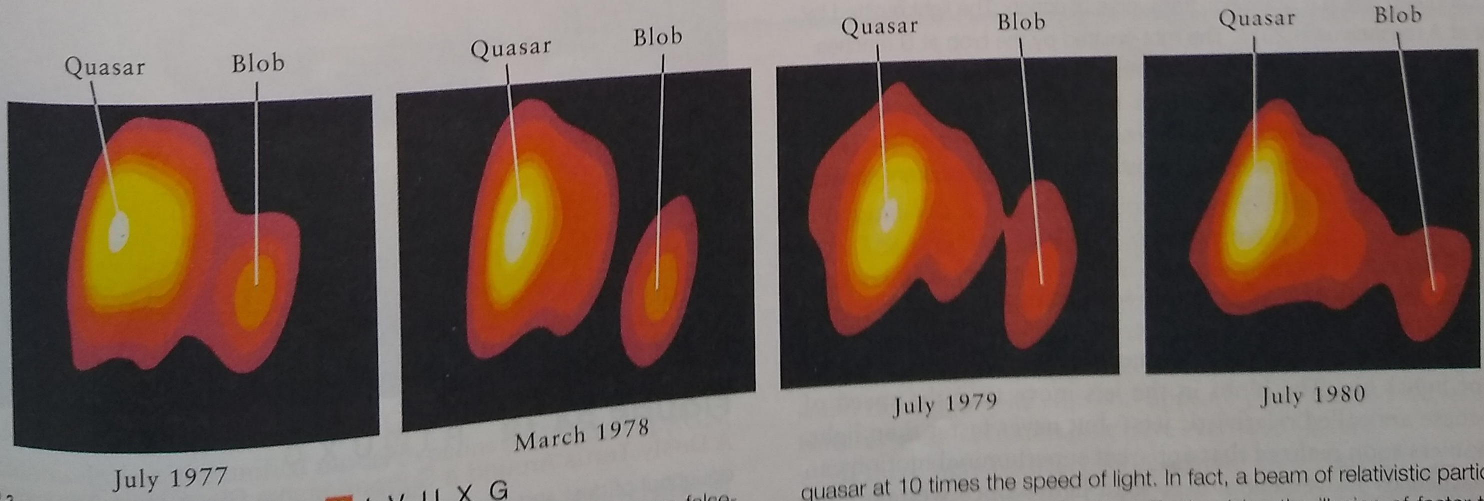
Nothing travels faster than the speed of light, but if something did, it would be called **superluminal motion.** Initially quite a mystery,



X ray
Optical
Radio continuum
Radio 21-cm emission

FIGURE 24-9 R I V U X G
Peculiar Galaxy NGC 5128 (Centaurus A) This extraordinary radio galaxy is located in the constellation Centaurus, 11 million ly from Earth. At visible wavelengths a dust lane crosses the face of the galaxy. Superimposed on this visible image is a false-color radio image (green) showing that vast quantities of radio emission pour from matter ejected from the galaxy perpendicular to the dust lane, along with radio emission (rose-colored) along the dust lane, and X-ray emission (blue) detected by NASA's Chandra X-ray Observatory. The X-rays may be from material ejected by the black hole or from the collision of Centaurus A with a smaller galaxy. Upper right inset: This X-ray image from the Einstein Observatory shows that NGC 5128 has a bright X-ray nucleus. An X-ra jet protrudes from the nucleus along a direction perpendicular to the galaxy's dust lane. (X-ray: NASA/CXC/M. Karovska et al.; radio 21-cm: NRAO/VLA/J. Van Gorkom Schminovich et al.; radio continuum: NRAO/VLA/J. Conden et al.; optical: Digitized Sky Survey U.K. Schmidt Image/STScI; inset: X-ray: NASA/CXC/Bristol U./M. Hardcastle; radio: RAO/VLA/Bristol U./M. Hardcastle)

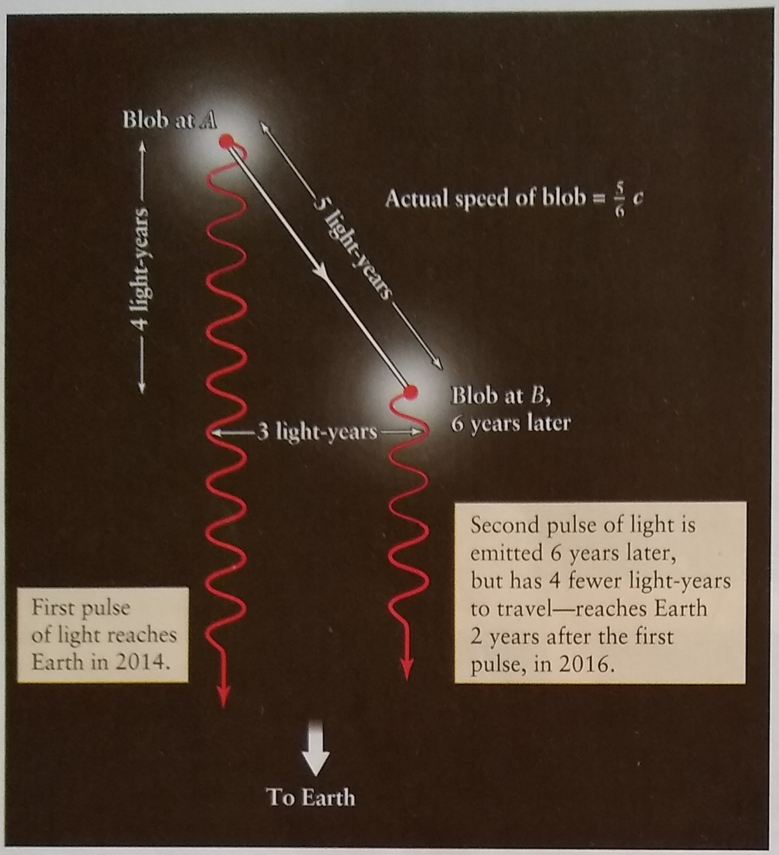
some quasars seemed to show superluminal motion when looking very closely at "blobs" of radio-emitting particles near the very base of their radio jets. For example, Figure 24-10 shows four high-resolution images of the quasar 3C 273 spanning three year During this interval, a blob moved away from the quasar at a rat of almost 0.001 arcsec per year. Taking into account the distanc



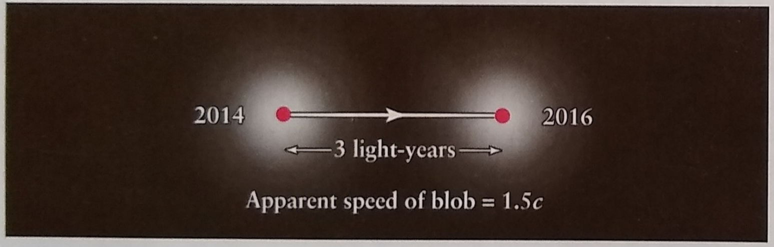
July 1977
March 1978
July 1979
July 1980

VIDEO 24-1

FIGURE 24-10 R I V U X G
Superluminal Motion in 3C 273 These four images are false-color, high-resolution radio maps of the quasar 3C 273 (shown in the image that opens this chapter). They show a blob that seems to move away from the quasar at 10 times the speed of light. In fact, a beam of relativistic particles f 3C 273 is aimed almost directly at Earth, giving the illusion of faster-than-l motion. Each image is about 7 milliarcseconds (0.007 arcsec) across. (NRAC



(a) View from above



(b) View from Earth

FIGURE 24-11

An Explanation of Superluminal Motion **(a)** If a blob of material ejected from a quasar moves at five-sixths of the speed of light, it covers the 5 ly from point A to point B in 6 years. In the case shown here, it moves 4 ly toward Earth and 3 ly in a sideways, transverse direction. The light emitted by the blob at A reaches us in 2014. The light emitted by the blob at B reaches us in 2016. The light left the blob at B 6 years later than the light from A but had 4 fewer light-years to travel to reach us. **(b)** From Earth we can see only the blob's sideways, transverse motion across the sky, as in Figure 24-10. It appears that the blob has traveled 3 ly in just 2 years, so its apparent speed is 3/2 of the speed of light, or 1.5c.

to the source, this rate of angular separation corresponds to a speed 10 times that of light!

Was Albert Einstein wrong that nothing travels faster than the speed of light? No. The blobs in the jets move near the speed of light—these are called relativistic jets—but never faster than light. Astronomers soon realized that apparent superluminal motion can be explained by movement slower than light—once we take into account the *angle* at which we view the relativistic jet.

In order to see material that appears to move faster t speed of light, two conditions must be met: The beam of must be aimed close to your line of sight (within about 5 de so), and material in the jet must travel near the speed of ligh the number of quasars with radio jets, it is not surprising th just happen to point toward us. Figure 24-11 shows how their geometry can produce apparent superluminal motion.

CONCEPTCHECK 24-6

In Figure 24-11, a bright blob appears to move faster th speed of light by traversing a 3-ly distance across the sl only 2 light-years. How far did the blob actually travel, a how long did it take?

Answer appears at the end of the chapter.

24-4 The unified model explains much o diversity of AGN

Untangling the mystery of active galactic nuclei was extraor difficult because AGN can appear very different from eacl In fact, it took several decades before researchers determin the diverse group of AGN could all be "unified" into one p model. Box 24-1 describes some different properties of AC their naming conventions. For example, one AGN, such as 3 might have a visible spectrum with unusually strong and

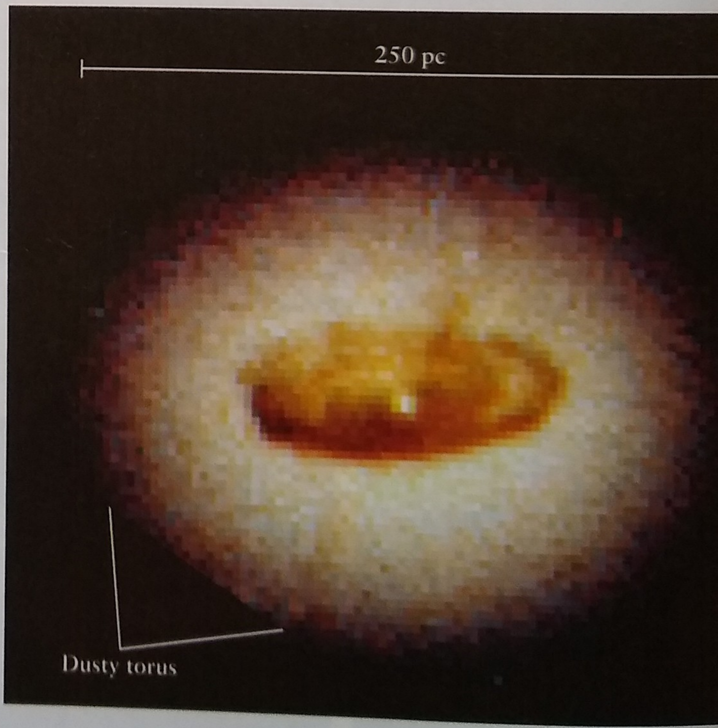


FIGURE 24-12 R I **V** U X G

A Dusty Torus Around a Supermassive Black Hole This imme doughnut of dust and gas orbits the black hole at the center of the activ galaxy NGC 4261. Radio jets emerge perpendicular to the plane of this (see Figure 21-16). (L. Ferrarese/Johns Hopkins University, NASA)

BOX 24-1 TOOLS OF THE ASTRONOMER'S TRADE

The Diversity of AGN

Active galactic nuclei, or AGN, come in two unique varieties: those with radio jets and lobes (called *radio-loud*), and those without (called *radio-quiet*). Radio galaxies, like those in Figures 24-1 and 24-8, are radio-loud AGN. About 10% of quasars are radio-loud, and, when observable, their host galaxies are elliptical. The remaining quasars are radio-quiet and, when observable, their hosts are spiral galaxies. (It is not understood why radio-loud and radio-quiet AGN are each found in ellipticals and spirals, respectively—this remains a mystery.)

The light emitted from jets is focused into a strong beam because the jets' emitting plasma travels near the speed of light. In cases where the jets are pointed almost directly toward Earth, the jets' beamed emission swamps the usual AGN emission, and these objects have a very different spectrum (often without any detected emission lines). These objects are called **blazars**, and while originally thought to be distinct from quasars due to their different appearance, they are now understood as special cases of jet alignment with our line of sight from Earth.

Quite similar to quasars, Seyfert galaxies also show bright, compact nuclei with emission lines. Eventually, it was realized that both quasars and Seyfert galaxies contain the same type of object, and both are examples of AGN. Historically, bright and distant AGN, where the host galaxies were not initially observed, are called quasars; nearby cases where the host galaxies can be easily seen are called Seyfert galaxies.

Seyfert galaxies and quasars also come in two further varieties: those with strong broad hydrogen emission lines (called Type 1) and those with weak narrow hydrogen emission lines (called Type 2). Furthermore, the continuum emission in the Type 1 AGN can vary significantly in brightness, whereas the continuum in the Type 2 AGN does not vary.

Explaining Type 1 and Type 2 AGN in terms of the *same central engine* was a major advance in understanding quasars, and the explanation is called the unified model. Ultimately, appearing as Type 1 or Type 2 depends on the line of sight, as shown in Figure 24-13. The table below summarizes some properties of AGN; the modern distinction of Type 1 or Type 2 is in parenthesis after the object's name.

Properties of Active Galactic Nuclei (AGN)

				Intrinsic Luminosity	
Object (Type)	Found in which type of galaxy	Strength of radio emission	Type of emission lines in spectrum	(watts)	(Milky Way Galaxy = 1)
Blazar (1)	Elliptical	Strong	None	10^{38} to 10^{42}	10 to 10^5
Radio-loud quasar (1)	Elliptical	Strong	Broad	10^{38} to 10^{42}	10 to 10^5
Radio galaxy (2)	Elliptical	Strong	Narrow	10^{36} to 10^{38}	0.1 to 10
Radio-quiet quasar (1)	Spiral or elliptical	Weak	Broad	10^{38} to 10^{42}	10 to 10^5
Type 1 Seyfert	Spiral	Weak	Broad	10^{36} to 10^{38}	0.1 to 10
Type 2 Seyfert	Spiral	Weak	Narrow	10^{36} to 10^{38}	0.1 to 10

hydrogen emission lines (Figure 24-3) and show strong variability (see Figure 24-5). Another AGN might have very weak and narrow hydrogen emission lines with little variability. Given the difficulty of explaining how one type of "central engine" powering their luminosity could explain such diverse behavior, these observations suggested—incorrectly—that these two AGN contain different emission mechanisms. In fact, the **unified model** explains how different AGN, at their core, are fundamentally the same.

The astronomer Robert Antonucci (now at University of California, Santa Barbara) put together the main picture of the unified model and uncovered its key ingredient: a thick dusty doughnut-shaped torus around the central engine's accretio disk. The presence of such a torus seems to be a natural result the overall accretion process. One such dusty torus is shown Figure 24-12. Rather than emitting visible light, the dusty toru can *block* light from passing through it from the central engine. contrast to the torus, the accretion disk within the torus is much t small to be seen—its emission appears pointlike—so no structur features of an accretion disk have ever been imaged.

If there were no dusty torus around an accreting supermassi black hole, an observer could view such a black hole from a angle and see the intense radiation from the accretion disk. B

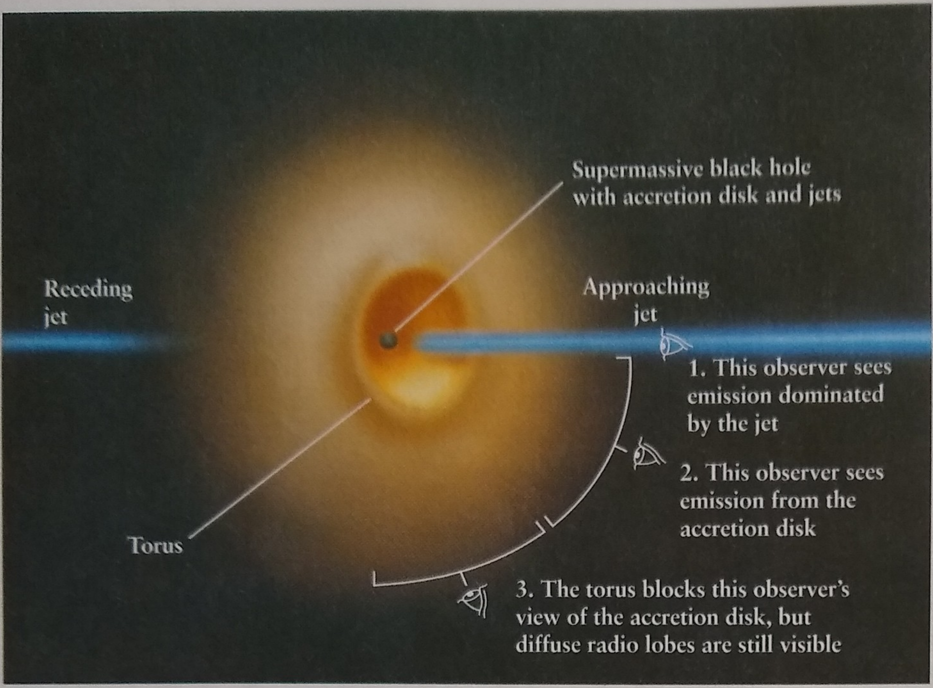


FIGURE 24-13

A Unified Model of Active Galaxies The AGN model consists of a supermassive black hole surrounde by an intensely luminous accretion disk. Farther out is a dusty doughnut-shaped torus. A pair of jets is also shown on this object, although not every AGN has jets. While this basic structure is at the heart of the randomly oriented AGN in space, each AGN can appear different depending on the viewing angle.

as a result of the torus, from certain angles the torus blocks the view of the accretion disk. This idea offers a single explanation for several types of seemingly different active galaxies.

Figure 24-13 illustrates the unified model for a luminous active galactic nucleus with radio jets. If an imaginary observer looks straight down the axis of the jet (#1), the observed radiation is dominated by the jet and has a unique spectrum with emission lines often undetected. (When viewed from this angle, an AGN is a blazar, as described in Box 24-1.)

At an intermediate angle (#2), the observer gets a clear view of the luminous accretion disk and the turbulent region around the black hole. Because gases move at many different velocities in this turbulent region, the observer sees hydrogen spectral lines (and other lines) that have been broadened by the Doppler effect. The observer also sees intense thermal radiation from the hot accretion disk. This line of sight, and the resulting features of the emission, account for the properties of quasar 3C 273 and the majority of quasars. (The Type 1 objects referred to in Box 24-1 are viewed from these intermediate angles.)

If the observer looks nearly edge-on at the torus (#3), the accretion disk is completely hidden. Some of the light reaching the observer comes from hot gas flowing out of the accretion disk, and this light has an emission-line spectrum. But given the edge-on orientation, this gas is not moving rapidly toward or away from the observer, so there is little Doppler shift and the hydrogen emission lines are narrow. (From this edge-on view, the AGN would be a Type 2 object as described in Box 24-1.) No radio jets are visible at this angle, but diffuse radio lobes are visible.

Unlike our imaginary observer, we cannot move the vast distances through space that would be needed to view a given active galaxy from different angles. Instead, we may see a given active galaxy differently, depending on how the accretion disk and torus are oriented to our line of sight. In other words, "What you see depends on the line of sight you get!"

CAUTION! Note that we are really making use of *tw* ferent but complementary models here. The unified mode that different types of active galactic nuclei are really dif views of the same type of "central engine," while the accr disk model explains how the "central engine" works.

CONCEPTCHECK 24-7

Is the large object in Figure 24-12 an accretion disk? Doe emit intense visible light?

CONCEPTCHECK 24-8

From which viewing angle in Figure 24-13 would an AGN appear bright in visible light and show broad emission line

Answers appear at the end of the chapter.

24-5 The evolution of AGN

The accretion-disk idea can explain what happens when galaxies collide or merge with other galaxies. Such collision mergers can transfer gas and dust from one galaxy to an providing more "fuel" for a supermassive black hole. For exa the image in Figure 24-14 shows a close-up view of a superm black hole about to take in more "fuel" from a merger. Th is not surprising that many of the most luminous active gal are also those that have recently undergone collisions, such radio galaxy Centaurus A shown in Figure 24-15.

The accretion disk idea also helps to explain why there a nearby quasars (see Figure 24-4). Over time, much of the avai gas and dust surrounding a quasar passes into the accretion and then enters the black hole. Eventually, the central engin less and less infalling matter to act as fuel, and the quasar bec

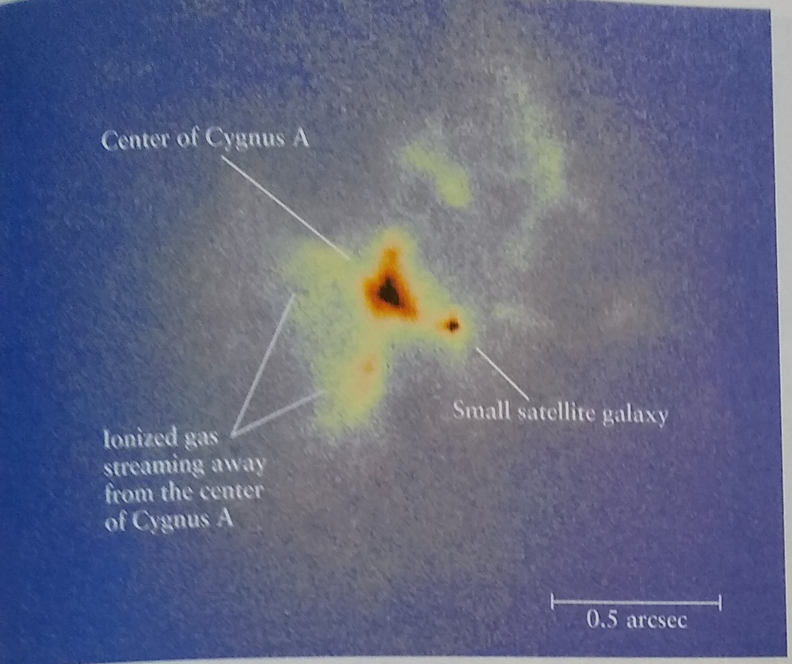


FIGURE 24-14 R I V U X G

Providing Fresh "Fuel" for a Supermassive Black Hole A small satellite galaxy has fallen into the central regions of the radio galaxy Cygnus A (see Figure 24-1). Its material may eventually accrete onto the supermassive black hole at Cygnus A's very center. This false-color extreme close-up was made using adaptive optics, described in Section 6-3. (Courtesy G. Canalizo, C. Max, D. Whysong, R. Antonucci, and S. E. Dahm)

inactive. Since quasars started shining in the early universe (about 12 billion years ago), and they consumed their fuel rather quickly (in a few hundred million years), the only quasars visible today in our expanding universe are very far away.

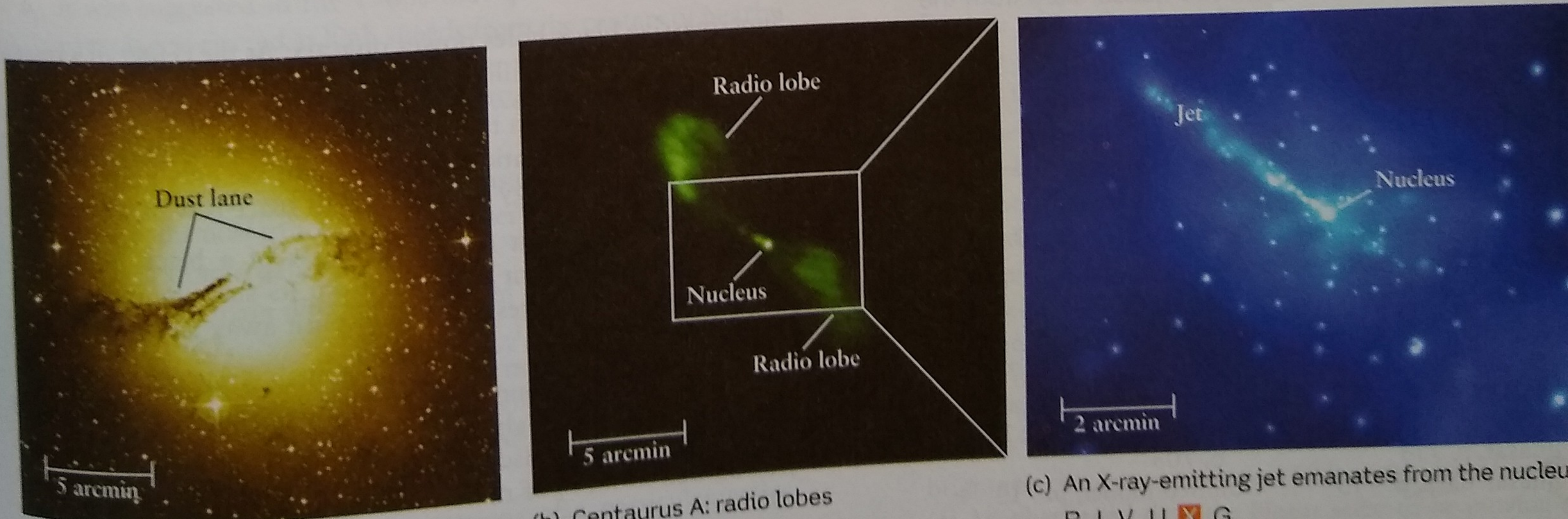
Dead Quasars and Flares

When a quasar runs out of accreting fuel altogether and becon inactive, some astronomers call the leftover supermassive bla hole a **dead quasar**. The vast majority of galaxies, including c own Milky Way, appear to have supermassive black holes at th centers that are not presently active. Therefore, dead quasars se to be in almost all luminous galaxies, so most galaxies once much more dramatic lives as quasars when they were young.

Is there a way to test the idea that most galaxies harbo supermassive black hole? Yes. Fortunately, there is a chance t a dead quasar can light up once again, even if only briefly. I star wanders too close to the supermassive black hole, tidal for (which act to stretch the star) can tear the star apart and pul some of its matter. This newly acquired stellar gas acts as tem rary accretion fuel for the otherwise dormant black hole. Moc of this process suggest that it might occur about once ev 10,000 years in a typical galaxy. As the star's matter is accre and is consumed by the black hole over a period of a year or s can shine brightly and is called a **dead quasar flare**.

Very few events provide convincing evidence for a flare. A all, there are other objects that can give a burst of light. One c for a flare came in March 2011, when a burst of X-rays (nar Swift J1644+57) was observed at the center of a galaxy. This f lasted only two days, but was observed from beginning to c The event was much brighter and shorter than expected for a t cal flare, and astronomers think the emission came from tem rarily formed jets, as opposed to an accretion disk (Figure 24-

Much is still unknown about quasars. How do they fo Does their visible light really come from an accretion d Why do some AGN have strong radio emission, while other not? What happens if a star wanders too close to a dead sar—does its captured gas form an accretion disk or jets? A



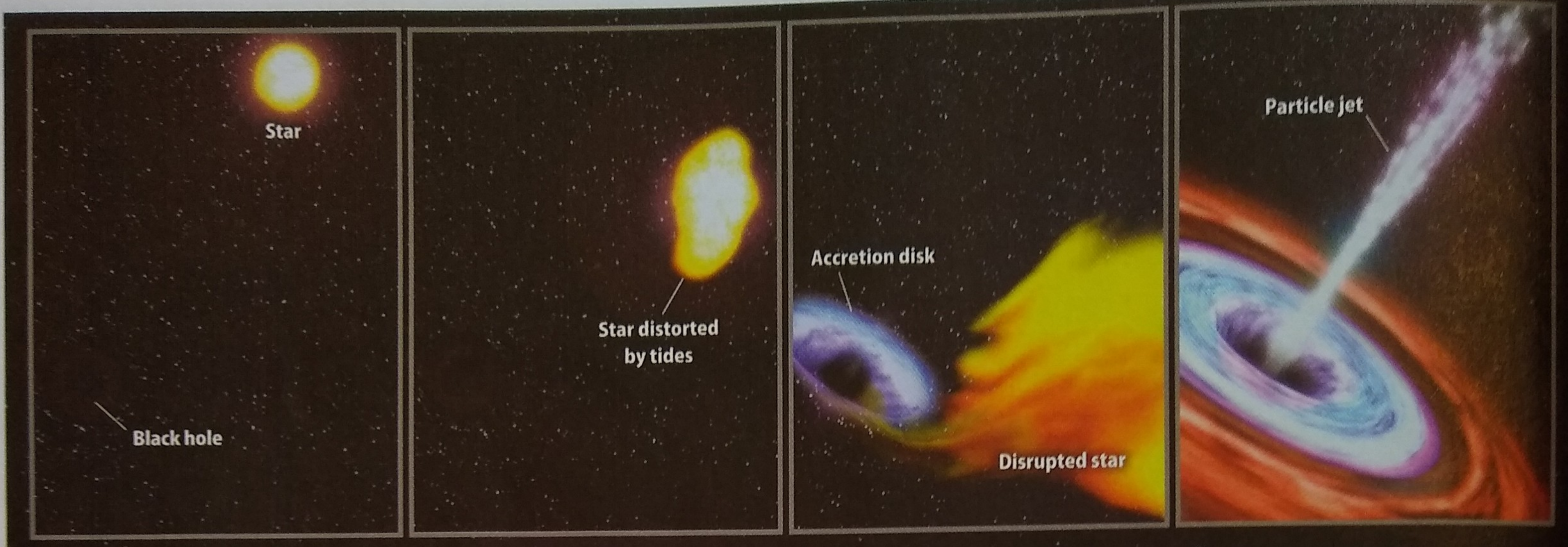
(a) Centaurus A: light from stars
R I V U X G

(b) Centaurus A: radio lobes
R I V U X G

(c) An X-ray-emitting jet emanates from the nucleu
R I V U X G

FIGURE 24-15

The Radio Galaxy Centaurus A (a) This elliptical galaxy, called NGC 5128, lies about 4 Mpc (13 million ly) from Earth at the location of the radio source Centaurus A. The dust lane is evidence of a collision with another galaxy. (b) At radio wavelengths we see synchrotron radiation from two radio lobes centered on the galaxy's nucleus. (c) A luminous jet extends from the nucleus directly toward one of the lobes. (a: Digitized Sky Survey/UK Schr Image/STScI; b: J. Condon et al./VLA/NRAO; c: R. Kraft et al./SAO/NASA)



1. A sun-like star on an eccentric orbit plunges toward the supermassive black hole in the heart of a distant galaxy.

2. Strong tidal forces near the black hole increasingly distort the star. If the star passes too close, it is ripped apart.

3. The part of the star facing the black hole streams toward it and forms an accretion disk. The remainder of the star just expands into space.

4. Near the black hole, magnetic fields power a narrow jet of particles moving near the speed of light. Viewed head-on, the jet is a brilliant X-ray and radio source.

FIGURE 24-16

Dead Quasar Flare A star wandering too close to a supermassive black hole can provide temporary fuel for the dead quasar. Modeling indicates that this event in 2012, called Swift J1644+57, occurred around a black hole about twice the mass of the 4 million solar mass black hole at the center of our Milky Way Galaxy. The X-ray emission from this flare lost most of its initial intensity over a period of several months. (NASA/Goddard Space Flight Center/Swift)

these questions are part of ongoing research in the field of active galaxies.

CONCEPTCHECK 24-9

Could our own Milky Way Galaxy have once hosted a quasar? If so, are we likely to witness a dead quasar flare from the center of our Milky Way Galaxy?

Answer appears at the end of the chapter.

KEY WORDS

Words preceded by an asterisk (*) are discussed in Box 24-1.

accretion, p. 706
accretion disk, p. 708
active galactic nucleus (AGN), p. 705
active galaxy, p. 705
*blazar, p. 713
dead quasar, p. 715
dead quasar flare, p. 715
Eddington limit, p. 707
quasar, p. 704
radio galaxy, p. 705
*Seyfert galaxy, p. 713
superluminal motion, p. 710
supermassive black hole, p. 708
unified model, p. 713

KEY IDEAS

Quasars or active galactic nuclei (AGN): A quasar looks like a star but has a huge redshift. According to the Hubble law, these redshifts show that quasars are typically billions of light-years away from Earth.

- To be seen at such large distances, quasars must be very lumi nous, typically about 1000 times brighter than an ordinary galax
- The peak of quasar activity took place when the universe wa just over 2 billion years old; the era of quasar activity has lon since passed.

Supermassive black holes power quasars: At the center of a quasa is a black hole with millions or even billions of solar masses.

- Rapid fluctuations in the brightness of quasars indicate that th region that emits radiation is quite small; the only known way t produce so much energy in such a small space is with a black hole
- The Eddington limit relates the mass of a black hole to the maximum luminosity it can emit from its surroundings; if mor luminous, radiation pressure would push away accreting gas an shut off the black hole's fuel source.

Accretion and jets around black holes: Hot gas accreting aroun the black hole is thought to give a quasar its intense luminosity About 10% of AGN also have strong radio emission coming fron jets, as well as lobes of radio emission as the jets collide with surrounding gas on scales much larger than the host galaxy.

- Models for a thin accretion disk describe heat and emission produced as portions of gas on different orbits rub past each other although no specific model of accretion has been verified.
- As gases spiral in toward the supermassive black hole, some of the gas may be redirected to form two jets of high-speed particles that are aligned perpendicularly to the accretion disk. When a jet is directed toward us, we can observe apparent superluminal motion.