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ACTIVE GALAXIES, QUASARS, AND SUPERMASSIVE BLACK HOLES

Figure 27.1 Hubble Ultra-Deep Field. The deepest picture of the sky in visible light (left) shows huge numbers of galaxies in a tiny patch of sky, only 1/100 the area of the full Moon. In contrast, the deepest picture of the sky taken in X-rays (right) shows large numbers of point-like quasars, which astronomers have shown are supermassive black holes at the very centers of galaxies. (credit left: modification of work by NASA, ESA, H. Teplitz and M. Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst (Arizona State University), and Z. Levay (STScI); credit right: modification of work by ESO/Mario Nonino, Piero Rosati, ESO GOODS Team)

Chapter Outline

- 27.1 Quasars
- 27.2 Supermassive Black Holes: What Quasars Really Are
- 27.3 Quasars as Probes of Evolution in the Universe



Thinking Ahead

During the first half of the twentieth century, astronomers viewed the universe of galaxies as a mostly peaceful place. They assumed that galaxies formed billions of years ago and then evolved slowly as the populations of stars within them formed, aged, and died. That placid picture completely changed in the last few decades of the twentieth century.

Today, astronomers can see that the universe is often shaped by violent events, including cataclysmic explosions of supernovae, collisions of whole galaxies, and the tremendous outpouring of energy as matter interacts in the environment surrounding very massive black holes. The key event that began to change our view of the universe was the discovery of a new class of objects: quasars.

27.1 QUASARS

Learning Objectives

By the end of this section, you will be able to:

- Describe how quasars were discovered
- Explain how astronomers determined that quasars are at the distances implied by their redshifts

- Justify the statement that the enormous amount of energy produced by quasars is generated in a very small volume of space

The name “quasars” started out as short for “quasi-stellar radio sources” (here “quasi-stellar” means “sort of like stars”). The discovery of radio sources that appeared point-like, just like stars, came with the use of surplus World War II radar equipment in the 1950s. Although few astronomers would have predicted it, the sky turned out to be full of strong sources of radio waves. As they improved the images that their new radio telescopes could make, scientists discovered that some radio sources were in the same location as faint blue “stars.” No known type of star in our Galaxy emits such powerful radio radiation. What then were these “quasi-stellar radio sources”?

Redshifts: The Key to Quasars

The answer came when astronomers obtained visible-light spectra of two of those faint “blue stars” that were strong sources of radio waves (**Figure 27.2**). Spectra of these radio “stars” only deepened the mystery: they had emission lines, but astronomers at first could not identify them with any known substance. By the 1960s, astronomers had a century of experience in identifying elements and compounds in the spectra of stars. Elaborate tables had been published showing the lines that each element would produce under a wide range of conditions. A “star” with unidentifiable lines in the ordinary visible light spectrum had to be something completely new.



Figure 27.2 Typical Quasar. The arrow in this image marks the quasar known by its catalog number, PKS 1117-248. Note that nothing in this image distinguishes the quasar from an ordinary star. Its spectrum, however, shows that it is moving away from us at a speed of 36% the speed of light, or 67,000 miles per second. In contrast, the maximum speed observed for any star is only a few hundred miles per second. (credit: modification of work by WIYN Telescope, Kitt Peak National Observatory, NOAO)

In 1963 at Caltech’s Palomar Observatory, Maarten Schmidt (**Figure 27.3**) was puzzling over the spectrum of one of the radio stars, which was named 3C 273 because it was the 273rd entry in the third Cambridge catalog of radio sources (part (b) of **Figure 27.3**). There were strong emission lines in the spectrum, and Schmidt recognized that they had the same spacing between them as the Balmer lines of hydrogen (see **Radiation and Spectra**). But the lines in 3C 273 were shifted far to the red of the wavelengths at which the Balmer lines are normally located. Indeed, these lines were at such long wavelengths that the redshifts were attributed to the Doppler effect, 3C 273 was receding from us at a speed of 45,000 kilometers per second, or about 15% the speed of light! Since stars don’t show Doppler shifts this large, no one had thought of considering high redshifts to be the cause of the strange spectra.

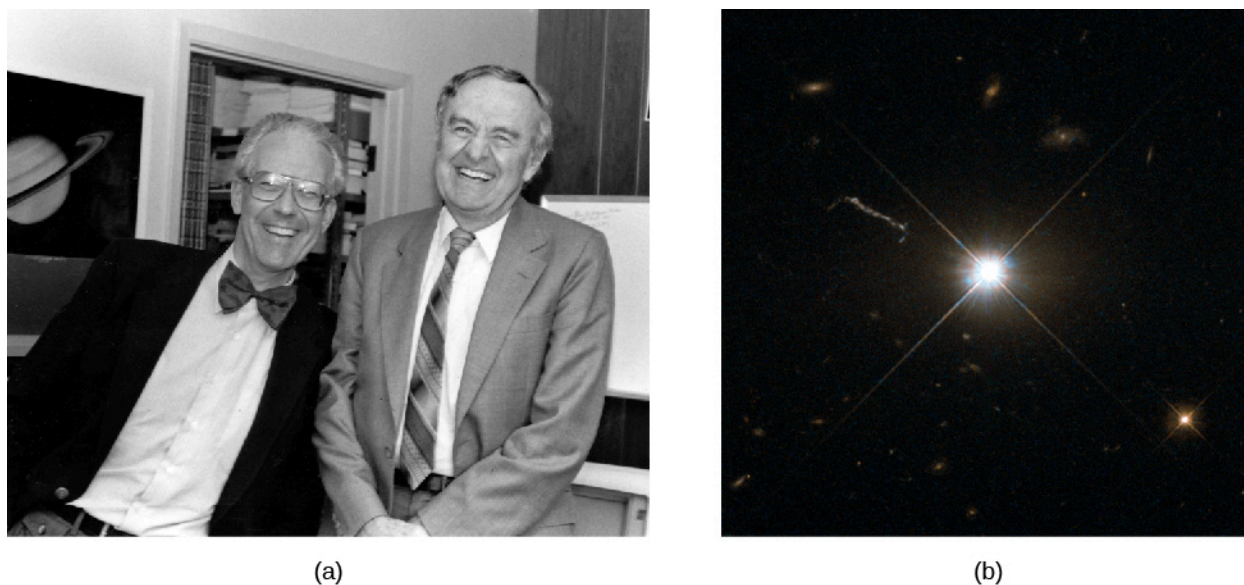


Figure 27.3 Quasar Pioneers and Quasar 3C 273. (a) Maarten Schmidt (left), who solved the puzzle of the quasar spectra in 1963, shares a joke in this 1987 photo with Allan Sandage, who took the first spectrum of a quasar. Sandage was also instrumental in measuring the value of Hubble's constant. (b) This is the first quasar for which a redshift was measured. The redshift showed that the light from it took about 2.5 billion years to reach us. Despite this great distance, it is still one of the quasars closest to the Milky Way Galaxy. Note also the faint streak going toward the upper left from the quasar. Some quasars, like 3C 273, eject super-fast jets of material. The jet from 3C 273 is about 200,000 light-years long. (credit a: modification of work by Andrew Fraknoi; credit b: modification of work by ESA/Hubble/NASA)

The puzzling emission lines in other star-like radio sources were then reexamined to see if they, too, might be well-known lines with large redshifts. This proved to be the case, but the other objects were found to be receding from us at even greater speeds. Their astounding speeds showed that the radio “stars” could not possibly be stars in our own Galaxy. Any true star moving at more than a few hundred kilometers per second would be able to overcome the gravitational pull of the Galaxy and completely escape from it. (As we shall see later in this chapter, astronomers eventually discovered that there was also more to these “stars” than just a point of light.)

It turns out that these high-velocity objects only look like stars because they are compact and very far away. Later, astronomers discovered objects with large redshifts that appear star-like but have no radio emission. Observations also showed that quasars were bright in the infrared and X-ray bands too, and not all these X-ray or infrared-bright quasars could be seen in either the radio or the visible-light bands of the spectrum. Today, all these objects are referred to as *quasi-stellar objects* (QSOs), or, as they are more popularly known, **quasars**. (The name was also soon appropriated by a manufacturer of home electronics.)

LINK TO LEARNING



Read [an interview \(https://openstax.org/l/30SchmidtIntv\)](https://openstax.org/l/30SchmidtIntv) with Maarten Schmidt on the fiftieth anniversary of his insight about the spectrum of quasars and their redshifts.

Over a million quasars have now been discovered, and spectra are available for over a hundred thousand. All these spectra show redshifts, none show blueshifts, and their redshifts can be very large. Yet in a photo they look just like stars ([Figure 27.4](#)).



Figure 27.4 Typical Quasar Imaged by the Hubble Space Telescope. One of these two bright “stars” in the middle is in our Galaxy, while the other is a quasar 9 billion light-years away. From this picture alone, there’s no way to say which is which. (The quasar is the one in the center of the picture.) (credit: Charles Steidel (CIT)/NASA/ESA)

In the record-holding quasars, the first Lyman series line of hydrogen, with a laboratory wavelength of 121.5 nanometers in the ultraviolet portion of the spectrum, is shifted all the way through the visible region to the infrared. At such high redshifts, the simple formula for converting a Doppler shift to speed ([Radiation and Spectra](#)) must be modified to take into account the effects of the theory of relativity. If we apply the relativistic form of the Doppler shift formula, we find that these redshifts correspond to velocities of about 96% of the speed of light.

EXAMPLE 27.1

Recession Speed of a Quasar

The formula for the Doppler shift, which astronomers denote by the letters z , is

$$z = \frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

where λ is the wavelength emitted by a source of radiation that is not moving, $\Delta\lambda$ is the difference between that wavelength and the wavelength we measure, v is the speed with which the source moves away, and c (as usual) is the speed of light.

A line in the spectrum of a galaxy is at a wavelength of 393 nanometers (nm, or 10^{-9} m) when the source is at rest. Let’s say the line is measured to be longer than this value (redshifted) by 7.86 nm. Then its redshift $z = \frac{7.86 \text{ nm}}{393 \text{ nm}} = 0.02$, so its speed away from us is 2% of the speed of light ($\frac{v}{c} = 0.02$).

This formula is fine for galaxies that are relatively nearby and are moving away from us slowly in the expansion of the universe. But the quasars and distant galaxies we discuss in this chapter are moving

away at speeds close to the speed of light. In that case, converting a Doppler shift (redshift) to a distance must include the effects of the special theory of relativity, which explains how measurements of space and time change when we see things moving at high speeds. The details of how this is done are way beyond the level of this text, but we can share with you the relativistic formula for the Doppler shift:

$$\frac{v}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}$$

Let's do an example. Suppose a distant quasar has a redshift of 5. At what fraction of the speed of light is the quasar moving away?

Solution

We calculate the following:

$$\frac{v}{c} = \frac{(5+1)^2 - 1}{(5+1)^2 + 1} = \frac{36 - 1}{36 + 1} = \frac{35}{37} = 0.946$$

The quasar is thus receding from us at about 95% the speed of light.

Check Your Learning

Several lines of hydrogen absorption in the visible spectrum have rest wavelengths of 410 nm, 434 nm, 486 nm, and 656 nm. In a spectrum of a distant galaxy, these same lines are observed to have wavelengths of 492 nm, 521 nm, 583 nm, and 787 nm respectively. What is the redshift of this galaxy? What is the recession speed of this galaxy?

Answer:

Because this is the same galaxy, we could pick any one of the four wavelengths and calculate how much it has shifted. If we use a rest wavelength of 410 nm and compare it to the shifted wavelength of 492 nm, we see that

$$z = \frac{\Delta\lambda}{\lambda} = \frac{(492 \text{ nm} - 410 \text{ nm})}{410 \text{ nm}} = \frac{82 \text{ nm}}{410 \text{ nm}} = 0.20$$

In the classical view, this galaxy is receding at 20% of the speed of light; however, at 20% of the speed of light, relativistic effects are starting to become important. So, using the relativistic Doppler equation, we compute the true recession rate as

$$\frac{v}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1} = \frac{(0.2+1)^2 - 1}{(0.2+1)^2 + 1} = \frac{1.44 - 1}{1.44 + 1} = \frac{0.44}{2.44} = 0.18$$

Therefore, the actual recession speed is only 18% of the speed of light. While this may not initially seem like a big difference from the classical measurement, there is already an 11% deviation between the classical and the relativistic solutions; and at greater recession speeds, the divergence between the classical and relativistic speeds increases rapidly!

Quasars Obey the Hubble Law

The first question astronomers asked was whether quasars obeyed the Hubble law and were really at the large distances implied by their redshifts. If they did not obey the rule that large redshift means large distance, then they could be much closer, and their luminosity could be a lot less. One straightforward way to show that

quasars had to obey the Hubble law was to demonstrate that they were actually part of galaxies, and that their redshift was the same as the galaxy that hosted them. Since ordinary galaxies *do* obey the Hubble law, anything within them would be subject to the same rules.

Observations with the Hubble Space Telescope provided the strongest evidence showing that quasars are located at the centers of galaxies. Hints that this is true had been obtained with ground-based telescopes, but space observations were required to make a convincing case. The reason is that quasars can outshine their entire galaxies by factors of 10 to 100 or even more. When this light passes through Earth's atmosphere, it is blurred by turbulence and drowns out the faint light from the surrounding galaxy—much as the bright headlights from an oncoming car at night make it difficult to see anything close by.

The Hubble Space Telescope, however, is not affected by atmospheric turbulence and can detect the faint glow from some of the galaxies that host quasars (**Figure 27.5**). Quasars have been found in the cores of both spiral and elliptical galaxies, and each quasar has the same redshift as its host galaxy. A wide range of studies with the Hubble Space Telescope now clearly demonstrate that quasars are indeed far away. If so, they must be producing a truly impressive amount of energy to be detectable as points of light that are much brighter than their galaxy. Interestingly, many quasar host galaxies are found to be involved in a collision with a second galaxy, providing, as we shall see, an important clue to the source of their prodigious energy output.

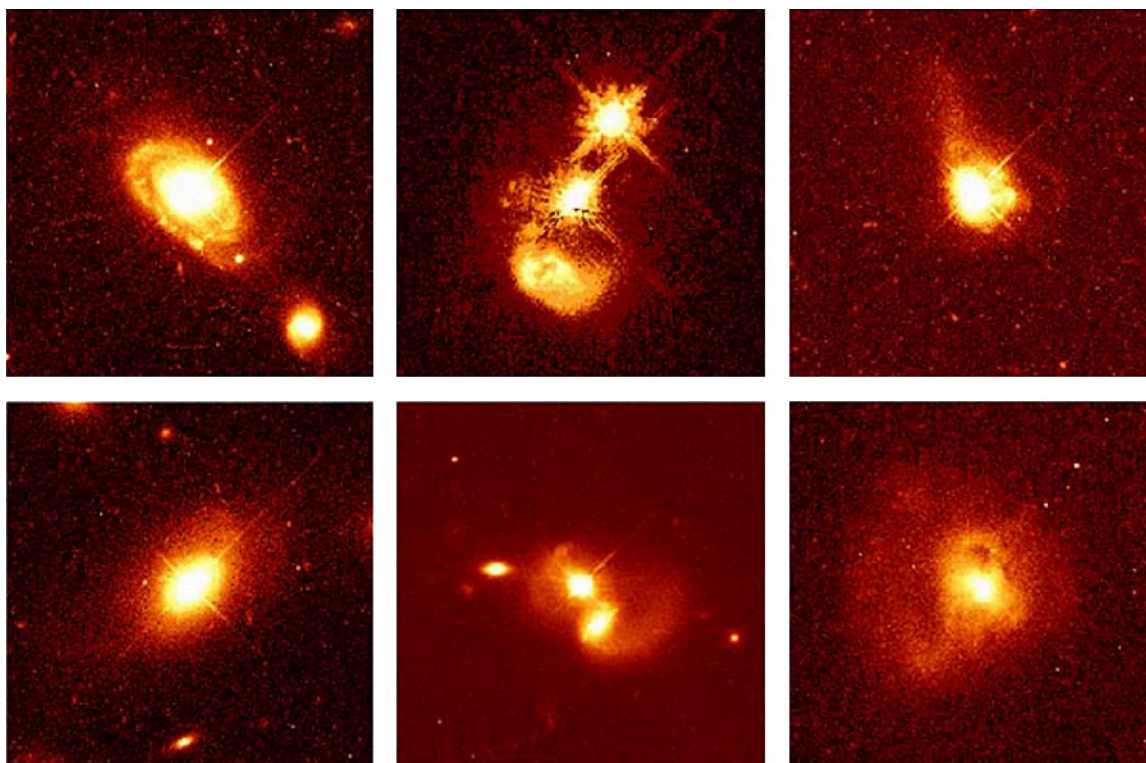


Figure 27.5 Quasar Host Galaxies. The Hubble Space Telescope reveals the much fainter “host” galaxies around quasars. The top left image shows a quasar that lies at the heart of a spiral galaxy 1.4 billion light-years from Earth. The bottom left image shows a quasar that lies at the center of an elliptical galaxy some 1.5 billion light-years from us. The middle images show remote pairs of interacting galaxies, one of which harbors a quasar. Each of the right images shows long tails of gas and dust streaming away from a galaxy that contains a quasar. Such tails are produced when one galaxy collides with another. (credit: modification of work by John Bahcall, Mike Disney, NASA)

The Size of the Energy Source

Given their large distances, quasars have to be extremely luminous to be visible to us at all—far brighter than any normal galaxy. In visible light alone, most are far more energetic than the brightest elliptical galaxies. But, as we saw, quasars also emit energy at X-ray and ultraviolet wavelengths, and some are radio sources as well. When all their radiation is added together, some QSOs have total luminosities as large as a hundred trillion Suns

($10^{14} L_{\text{Sun}}$), which is 10 to 100 times the brightness of luminous elliptical galaxies.

Finding a mechanism to produce the large amount of energy emitted by a quasar would be difficult under any circumstances. But there is an additional problem. When astronomers began monitoring quasars carefully, they found that some vary in luminosity on time scales of months, weeks, or even, in some cases, days. This variation is irregular and can change the brightness of a quasar by a few tens of percent in both its visible light and radio output.

Think about what such a change in luminosity means. A quasar at its dimmest is still more brilliant than any normal galaxy. Now imagine that the brightness increases by 30% in a few weeks. Whatever mechanism is responsible must be able to release new energy at rates that stagger our imaginations. The most dramatic changes in quasar brightness are equivalent to the energy released by 100,000 billion Suns. To produce this much energy we would have to convert the total mass of about ten Earths into energy every minute.

Moreover, because the fluctuations occur in such short times, the part of a quasar that is varying must be smaller than the distance light travels in the time it takes the variation to occur—typically a few months. To see why this must be so, let's consider a cluster of stars 10 light-years in diameter at a very large distance from Earth (see [Figure 27.6](#), in which Earth is off to the right). Suppose every star in this cluster somehow brightens simultaneously and remains bright. When the light from this event arrives at Earth, we would first see the brighter light from stars on the near side; 5 years later we would see increased light from stars at the center. Ten years would pass before we detected more light from stars on the far side.

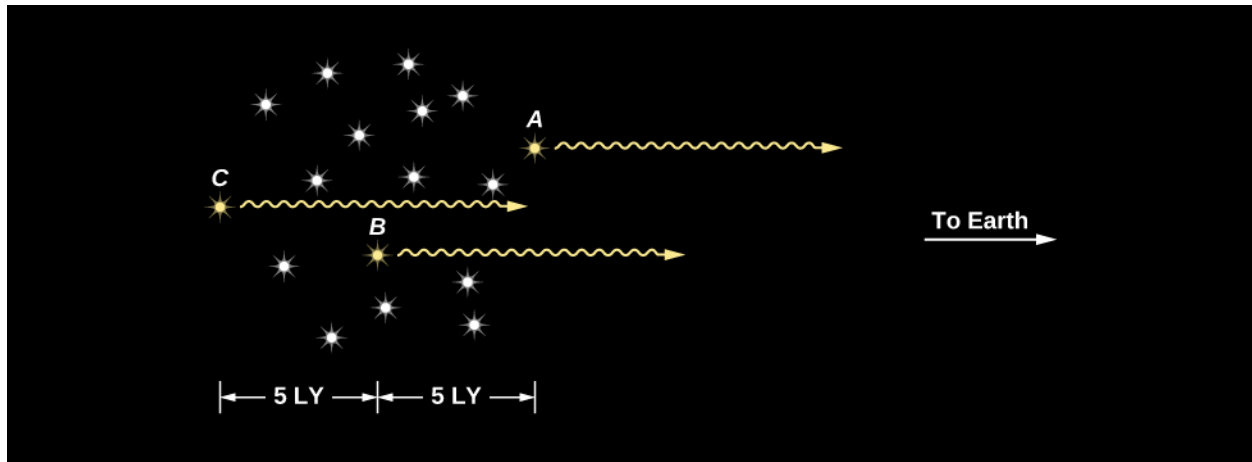


Figure 27.6 How the Size of a Source Affects the Timescale of Its Variability. This diagram shows why light variations from a large region in space appear to last for an extended period of time as viewed from Earth. Suppose all the stars in this cluster, which is 10 light-years across, brighten simultaneously and instantaneously. From Earth, star A will appear to brighten 5 years before star B, which in turn will appear to brighten 5 years earlier than star C. It will take 10 years for an Earth observer to get the full effect of the brightening.

Even though all stars in the cluster brightened at the same time, the fact that the cluster is 10 light-years wide means that 10 years must elapse before the increased light from every part of the cluster reaches us. From Earth we would see the cluster get brighter and brighter, as light from more and more stars began to reach us. Not until 10 years after the brightening began would we see the cluster reach maximum brightness. In other words, if an extended object suddenly flares up, it will seem to brighten over a period of time equal to the time it takes light to travel across the object from its far side.

We can apply this idea to brightness changes in quasars to estimate their diameters. Because quasars typically vary (get brighter and dimmer) over periods of a few months, the region where the energy is generated can be no larger than a few light-months across. If it were larger, it would take longer than a few months for the light from the far side to reach us.

How large is a region of a few light-months? Pluto, usually the outermost (dwarf) planet in our solar system, is about 5.5 light-hours from us, while the nearest star is 4 light-years away. Clearly a region a few light months across is tiny relative to the size of the entire Galaxy. And some quasars vary even more rapidly, which means their energy is generated in an even smaller region. Whatever mechanism powers the quasars must be able to generate more energy than that produced by an entire galaxy in a volume of space that, in some cases, is not much larger than our solar system.

Earlier Evidence

Even before the discovery of quasars, there had been hints that something very strange was going on in the centers of at least some galaxies. Back in 1918, American astronomer Heber Curtis used the large Lick Observatory telescope to photograph the galaxy Messier 87 in the constellation Virgo. On that photograph, he saw what we now call a jet coming from the center, or nucleus, of the galaxy (**Figure 27.7**). This jet literally and figuratively pointed to some strange activity going on in that galaxy nucleus. But he had no idea what it was. No one else knew what to do with this space oddity either.

The random factoid that such a central jet existed lay around for a quarter century, until Carl Seyfert, a young astronomer at Mount Wilson Observatory, also in California, found half a dozen galaxies with extremely bright nuclei that were almost stellar, rather than fuzzy in appearance like most galaxy nuclei. Using spectroscopy, he found that these nuclei contain gas moving at up to two percent the speed of light. That may not sound like much, but it is 6 million miles per hour, and more than 10 times faster than the typical motions of stars in galaxies.

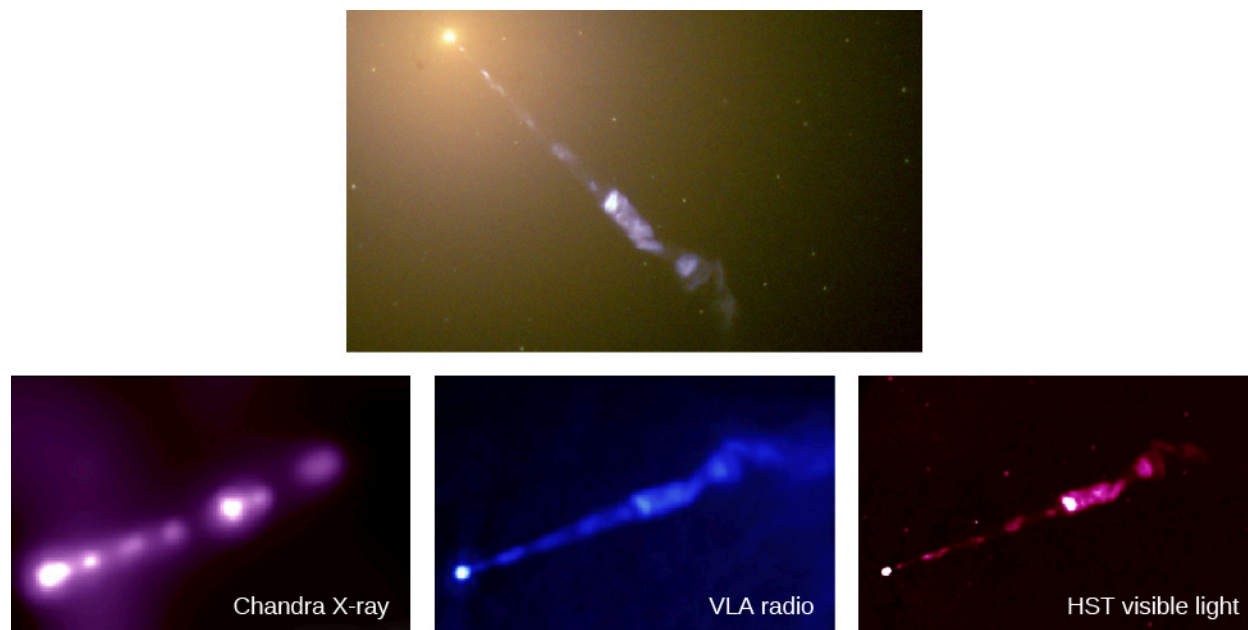


Figure 27.7 M87 Jet. Streaming out like a cosmic searchlight from the center of the galaxy, M87 is one of nature’s most amazing phenomena, a huge jet of electrons and other particles traveling at nearly the speed of light. In this Hubble Space Telescope image, the blue of the jet contrasts with the yellow glow from the combined light of billions of unseen stars and yellow, point-like globular clusters that make up the galaxy (at the upper left). As we shall see later in this chapter, the jet, which is several thousand light-years long, originates in a disk of superheated gas swirling around a giant black hole at the center of M87. The light that we see is produced by electrons twisting along magnetic field lines in the jet, a process known as synchrotron radiation, which gives the jet its bluish tint. The jet in M87 can be observed in X-ray, radio, and visible light, as shown in the bottom three images. At the extreme left of each bottom image, we see the bright galactic nucleus harboring a supermassive black hole. (credit top: modification of work by NASA, The Hubble Heritage Team(STScI/AURA); credit bottom: modification of work by X-ray: H. Marshall (MIT), et al., CXC, NASA; Radio: F. Zhou, F. Owen (NRAO), J. Biretta (STScI); Optical: E. Perlman (UMBC), et al.)

After decades of study, astronomers identified many other strange objects beyond our Milky Way Galaxy; they populate a whole “zoo” of what are now called **active galaxies** or **active galactic nuclei (AGN)**. Astronomers

first called them by many different names, depending on what sorts of observations discovered each category, but now we know that we are always looking at the same basic mechanism. What all these galaxies have in common is some activity in their nuclei that produces an enormous amount of energy in a very small volume of space. In the next section, we describe a model that explains all these galaxies with strong central activity—both the AGNs and the QSOs.

LINK TO LEARNING



To see a jet for yourself, check out a [time-lapse video \(https://openstax.org/l/30timelapsejet\)](https://openstax.org/l/30timelapsejet) of the jet ejected from NGC 3862.

27.2 SUPERMASSIVE BLACK HOLES: WHAT QUASARS REALLY ARE

Learning Objectives

By the end of this section, you will be able to:

- › Describe the characteristics common to all quasars
- › Justify the claim that supermassive black holes are the source of the energy emitted by quasars (and AGNs)
- › Explain how a quasar's energy is produced

In order to find a common model for quasars (and their cousins, the AGNs), let's first list the common characteristics we have been describing—and add some new ones:

- Quasars are hugely powerful, emitting more power in radiated light than all the stars in our Galaxy combined.
- Quasars are tiny, about the size of our solar system (to astronomers, that is really small!).
- Some quasars are observed to be shooting out pairs of straight jets at close to the speed of light, in a tight beam, to distances far beyond the galaxies they live in. These jets are themselves powerful sources of radio and gamma-ray radiation.
- Because quasars put out so much power from such a small region, they can't be powered by nuclear fusion the way stars are; they must use some process that is far more efficient.
- As we shall see later in this chapter, quasars were much more common when the universe was young than they are today. That means they must have been able to form in the first billion years or so after the universe began to expand.

The readers of this text are in a much better position than the astronomers who discovered quasars in the 1960s to guess what powers the quasars. That's because the key idea in solving the puzzle came from observations of the black holes. The discovery of the first stellar mass black hole in the binary system Cygnus X-1 was announced in 1971, several years after the discovery of quasars. Proof that there is a black hole at the center of our own Galaxy came even later. Back when astronomers first began trying to figure out what powered quasars, black holes were simply one of the more exotic predictions of the general theory of relativity that still waited to be connected to the real world.