FIGURE 19.19 This painting shows a model of how the Milky Way's halo may have formed. The characteristics of stars in the Milky Way's halo suggest that several smaller gas clouds, already bearing some stars and globular clusters, may have merged to form the Milky Way's protogalactic cloud. These stars and star clusters remained in the halo while the gas settled into the Milky Way's disk.

Dwarf and Canis Major Dwarf galaxies are currently crashing through the Milky Way's disk and are being torn apart in the process. A billion years from now, their stars will be indistinguishable from halo stars because they will all be circling the Milky Way on orbits that carry them high above the disk. Evidence indicates that this process has also occurred in the past: Some halo stars move in organized streams that are probably the remnants of dwarf galaxies torn apart long ago by the Milky Way's gravity.

THINK ABOUT IT

If the preceding scenario is true, then the Milky Way suffered several collisions early in its history. Explain why we should not be surprised that galaxy collisions (or collisions between protogalactic clouds) were rather common in the distant past. (*Hint:* How did the average separations of galaxies in the past compare to their average separations today?)

The distribution of heavy elements in the Milky Way's disk and bulge suggests that when the disk finally formed, it began with only about 10% of the amount of heavy elements that it has today, but with a greater concentration of heavy elements near the center. Observations of old stars in the bulge of our galaxy show that the clouds from which the bulge stars formed had a chemical composition similar to that of our Sun, even though they gave birth to those stars over 10 billion years ago.

Evidence indicates that after the Milky Way's disk was in place, the star–gas–star cycle gradually increased the disk's heavy-element content in a more orderly fashion. Because the star–gas–star cycle has been operating continuously in the Milky Way's disk ever since the disk formed, the ages of disk stars range from newly born to 10 billion or more years old. We expect star formation to continue in the disk as long as enough gas remains within it.

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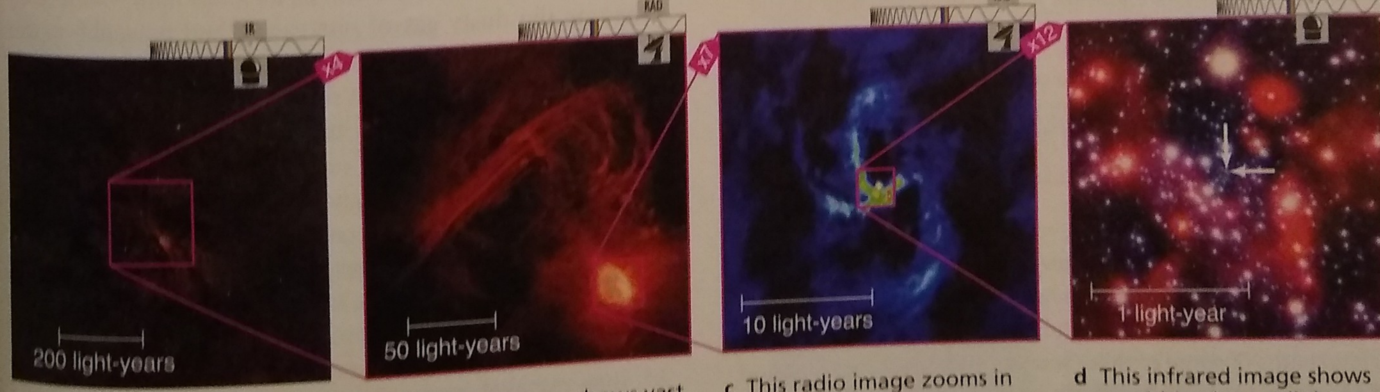
19.4 THE MYSTERIOUS GALACTIC CENTER

The center of the Milky Way Galaxy lies in the direction of the constellation Sagittarius. This region of the sky does not look particularly special to our unaided eyes. However, if we could remove the interstellar dust that obscures our view, the galaxy's central bulge would be one of the night sky's most spectacular sights. And deep within the bulge, at the very center of the Milky Way, sits one of the most mysterious objects in our galaxy.

What lies in the center of our galaxy?

Although the Milky Way's clouds of gas and dust prevent us from seeing visible light from the center of the galaxy, we can peer into the heart of our galaxy with radio, infrared, and X-ray telescopes. FIGURE 19.20 shows a series of infrared and radio views looking ever deeper into the galaxy's center.



a This infrared image shows stars and gas clouds within 1000 light-years of the center of the Milky Way.

b This radio image shows vast threads of emission tracing magnetic field lines near the galactic center.

c This radio image zooms in on gas swirling around the radio source Sgr A* (white dot), suspected to contain a very massive black hole.

d This infrared image shows stars within about 1 light-year of Sgr A*. The two arrows point to the precise location of Sgr A*.

FIGURE 19.20 **interactive photo** Zooming into the galactic center at infrared and radio wavelengths.

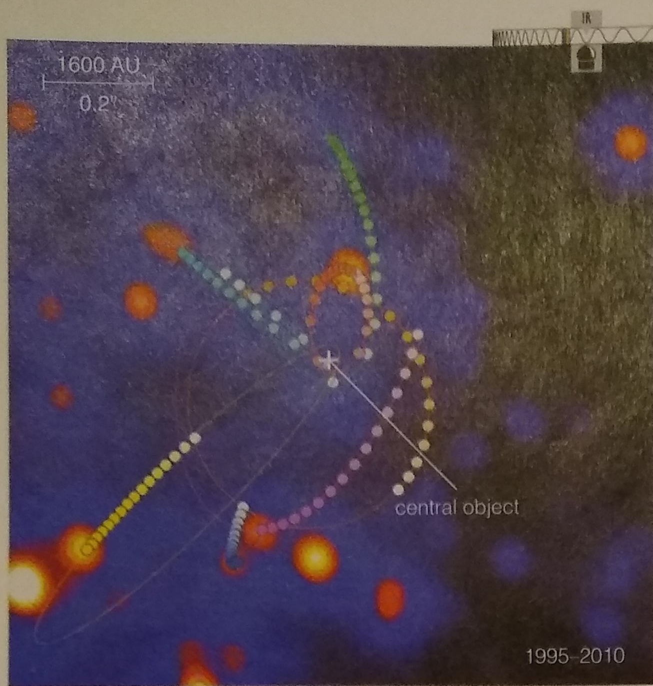


FIGURE 19.21 Evidence for a black hole at the center of our galaxy. Each set of colored dots shows the positions of a particular star at 1-year intervals as observed with the Keck Telescope. Calculated orbits for these stars are also shown. By applying Newton's version of Kepler's third law to these orbits, we infer that the central object has a mass about 4 million times that of our Sun, packed into a space so small that it is almost certainly a black hole. (The 1600 AU shown on the scale bar is equivalent to about 9 light-days.)

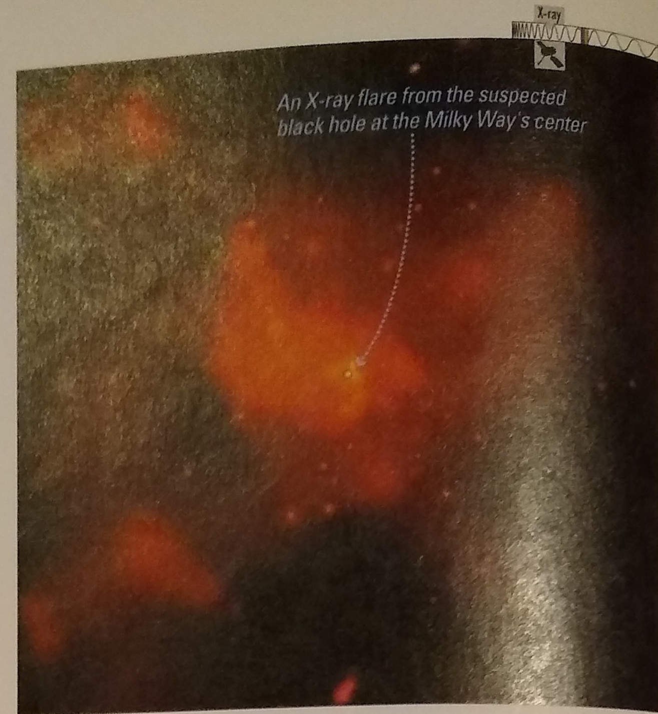


FIGURE 19.22 This X-ray image from the Chandra X-Ray Observatory shows the central 60 light-years of our galaxy and an X-ray flare from the massive black hole thought to reside there.

Within about 1000 light-years of the center, we find swirling clouds of gas and a cluster of several million stars. Bright radio emission traces out the magnetic fields that thread this turbulent region. In the exact center, we find a source of radio emission named Sagittarius A* (pronounced "Sagittarius A-star"), or Sgr A* for short, which is quite unlike any other radio source in our galaxy.

SEE IT FOR YOURSELF

Use the star charts in Appendix I (or a star-finding app) to find the constellation Sagittarius, which is easily visible on summer and fall evenings and looks like a teapot with a handle on the left and a spout on the right. The center of the Milky Way Galaxy is near the tip of the spout. Can you see the Milky Way's faint band of light passing through the constellations Sagittarius, Cygnus, and Cassiopeia?

Several hundred stars crowd the region within about 1 light-year of Sgr A*, and their motions indicate the presence of an extremely massive object. FIGURE 19.21 shows the orbital paths of some of these stars as measured over a period of 15 years. Applying Newton's version of Kepler's third law to the orbits of these stars shows that this object must have a mass of about 4 million solar masses, all packed into a region of space just a little larger than our solar system. An object that massive within such a small space is almost certainly a black hole.

However, the behavior of this suspected black hole is rather puzzling. Most other suspected black holes are thought to accumulate matter through accretion disks that radiate brightly in X rays. These include black holes in binary star systems like Cygnus X-1 [**Section 18.3**] and some giant black holes at the centers of other galaxies, which we will discuss in Chapter 21. If the black hole at the center of our galaxy had an accretion disk like these others, its X-ray light would easily penetrate the dusty gas of our galaxy and it would appear fairly bright to our X-ray telescopes. Yet the X-ray emission from Sgr A* has usually been relatively faint.

Observations made in other wavelengths of light are helping us understand this surprising behavior. For example, enormous X-ray flares have been observed coming from the location of the suspected black hole (FIGURE 19.22). These sudden changes in brightness probably come from comet-size lumps of matter torn apart by the black hole's tidal forces just before disappearing beneath its event horizon. If we continue to observe similar X-ray flares from Sgr A*, then the explanation for its generally low X-ray brightness may be that matter falls into it in big chunks instead of in the smooth, swirling flow of an accretion disk. Until we better understand Sgr A*, it is sure to remain a favorite target for observation.

The Big Picture

Putting Chapter 19 into Context

In this chapter, we have explored the structure, motion, and history of our galaxy, along with the recycling of gas that has made our existence possible. When you review this chapter, pay attention to these "big picture" ideas:

- The inability of visible light to penetrate deeply through interstellar gas and dust concealed the true nature of our galaxy until recent times. Modern astronomical instruments reveal the Milky Way Galaxy to be a dynamic system of stars and gas that continually gives birth to new stars and planetary systems.
- Stellar winds and explosions make interstellar space a violent place. Hot gas tears through the atomic hydrogen gas that fills much of the galactic disk, leaving expanding bubbles and fast-moving clouds in its wake. All this violence might seem quite dangerous, but it performs the great service of mixing new heavy elements into the gas of the Milky Way.
- Although the elements from which we are made were forged in stars, we could not exist if stars were not organized into galaxies. The Milky Way Galaxy acts as a giant recycling plant, converting gas expelled from each generation of stars into the next generation and allowing some of the heavy elements to solidify into planets like our own.

SUMMARY OF KEY CONCEPTS

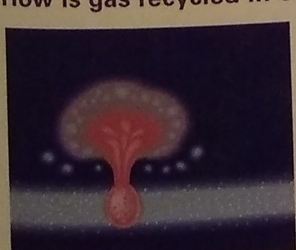
19.1 THE MILKY WAY REVEALED

- **What does our galaxy look like?** The Milky Way Galaxy is a **spiral galaxy** consisting of a thin **disk** about 100,000 light-years in diameter with a central **bulge** and a spherical region called the **halo** that surrounds the entire disk. The disk contains most of the gas and dust of the interstellar medium, while the halo contains only a small amount of hot gas and virtually no cold gas.

- **How do stars orbit in our galaxy?** Stars in the disk all orbit the galactic center in about the same plane and in the same direction. Halo and bulge stars also orbit the center of the galaxy, but their orbits are randomly inclined to the disk of the galaxy. Orbital motions of stars allow us to determine the distribution of mass in our galaxy.

19.2 GALACTIC RECYCLING

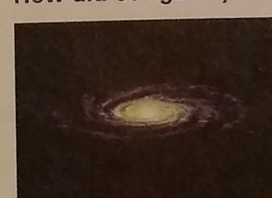
- **How is gas recycled in our galaxy?** Stars are born from the gravitational collapse of gas clumps in molecular clouds. Massive stars explode as supernovae when they die, creating hot **bubbles** in the interstellar medium that contain the new elements made by these stars. Eventually, this gas cools and mixes into the surrounding interstellar medium, turning into **atomic hydrogen gas** and then cooling further, producing molecular clouds. These molecular clouds then form stars, completing the **star–gas–star cycle**.



- **Where do stars tend to form in our galaxy?** Active star-forming regions, marked by the presence of hot massive stars and **ionization nebulae**, are found preferentially in **spiral arms**. The spiral arms represent regions where a **spiral density wave** has caused gas clouds to crash into each other, thereby compressing them and making star formation more likely.

19.3 THE HISTORY OF THE MILKY WAY

- **What clues to our galaxy's history do halo stars hold?** The stars of the bulge and the halo, together known as the **spheroidal population** of stars, are old low-mass stars with a much smaller proportion of heavy elements than stars in the **disk population**. Halo stars therefore must have formed early in the galaxy's history, before the gas settled into a disk.
- **How did our galaxy form?** Halo stars probably formed in several different **protogalactic clouds** of hydrogen and helium gas. Gravity pulled those clouds and stars together to form a single larger cloud of stars and gas. The collapse of this cloud continued until it formed a spinning disk around the galactic center. Stars have formed continuously in the disk since that time, but stars no longer form in the halo.



19.4 THE MYSTERIOUS GALACTIC CENTER

- **What lies in the center of our galaxy?** Orbits of stars near the center of our galaxy suggest that it contains a black hole about 4 million times as massive as the Sun. The black hole appears to be powering a bright source of radio emission known as Sgr A*.