

study of astronomy so far. Since this matter is invisible, it clearly cannot be in the form of ordinary stars. And it cannot be gas in any form (remember that there has to be a lot of it). If it were neutral hydrogen gas, its 21-cm wavelength spectral-line emission would have been detected as radio waves. If it were ionized hydrogen, it should be hot enough to emit visible radiation. If a lot of hydrogen atoms out there had combined into hydrogen molecules, these should produce dark features in the ultraviolet spectra of objects lying beyond the Galaxy, but such features have not been seen. Nor can the dark matter consist of interstellar dust, since in the required quantities, the dust would significantly obscure the light from distant galaxies.

What are our other possibilities? The dark matter cannot be a huge number of black holes (of stellar mass) or old neutron stars, since interstellar matter falling onto such objects would produce more X-rays than are observed. Also, recall that the formation of black holes and neutron stars is preceded by a substantial amount of mass loss, which scatters heavy elements into space to be incorporated into subsequent generations of stars. If the dark matter consisted of an enormous number of any of those objects, they would have blown off and recycled a lot of heavier elements over the history of the Galaxy. In that case, the young stars we observe in our Galaxy today would contain much greater abundances of heavy elements than they actually do.

Brown dwarfs and lone Jupiter-like planets have also been ruled out. First of all, there would have to be an awful lot of them to make up so much dark matter. But we have a more direct test of whether so many low-mass objects could actually be lurking out there. As we learned in [Black Holes and Curved Spacetime](#), the general theory of relativity predicts that the path traveled by light is changed when it passes near a concentration of mass. It turns out that when the two objects appear close enough together in the sky, the mass closer to us can bend the light from farther away. With just the right alignment, the image of the more distant object also becomes significantly brighter. By looking for the temporary brightening that occurs when a dark matter object in our own Galaxy moves across the path traveled by light from stars in the Magellanic Clouds, astronomers have now shown that the dark matter cannot be made up of a lot of small objects with masses between one-millionth and one-tenth the mass of the Sun.

What's left? One possibility is that the dark matter is composed of exotic subatomic particles of a type not yet detected on Earth. Very sophisticated (and difficult) experiments are now under way to look for such particles. Stay tuned to see whether anything like that turns up.

We should add that the problem of dark matter is by no means confined to the Milky Way. Observations show that dark matter must also be present in other galaxies (whose outer regions also orbit too fast “for their own good”—they also have flat rotation curves). As we will see, dark matter even exists in great clusters of galaxies whose members are now known to move around under the influence of far more gravity than can be accounted for by luminous matter alone.

Stop a moment and consider how astounding the conclusion we have reached really is. Perhaps as much as 95% of the mass in our Galaxy (and many other galaxies) is not only invisible, but we do not even know what it is made of. The stars and raw material we can observe may be merely the tip of the cosmic iceberg; underlying it all may be other matter, perhaps familiar, perhaps startlingly new. Understanding the nature of this dark matter is one of the great challenges of astronomy today; you will learn more about this in [A Universe of \(Mostly\) Dark Matter and Dark Energy](#).

25.4 THE CENTER OF THE GALAXY

Learning Objectives

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

- › Describe the radio and X-ray observations that indicate energetic phenomena are occurring at the galactic

center

- › Explain what has been revealed by high-resolution near-infrared imaging of the galactic center
- › Discuss how these near-infrared images, when combined with Kepler's third law of motion, can be used to derive the mass of the central gravitating object

At the beginning of this chapter, we hinted that the core of our Galaxy contains a large concentration of mass. In fact, we now have evidence that the very center contains a black hole with a mass equivalent to 4.6 million Suns and that all this mass fits within a sphere that has less than the diameter of Mercury's orbit. Such monster black holes are called **supermassive black holes** by astronomers, to indicate that the mass they contain is far greater than that of the typical black hole created by the death of a single star. It is amazing that we have very convincing evidence that this black hole really does exist. After all, recall from the chapter on **Black Holes and Curved Spacetime** that we cannot see a black hole directly because by definition it radiates no energy. And we cannot even see into the center of the Galaxy in visible light because of absorption by the interstellar dust that lies between us and the galactic center. Light from the central region of the Galaxy is dimmed by a factor of a trillion (10^{12}) by all this dust.

Fortunately, we are not so blind at other wavelengths. Infrared and radio radiation, which have long wavelengths compared to the sizes of the interstellar dust grains, flow unimpeded past the dust particles and so reach our telescopes with hardly any dimming. In fact, the very bright radio source in the nucleus of the Galaxy, now known as Sagittarius A* (pronounced "Sagittarius A-star" and abbreviated Sgr A*), was the first cosmic radio source astronomers discovered.

A Journey toward the Center

Let's take a voyage to the mysterious heart of our Galaxy and see what's there. **Figure 25.14** is a radio image of a region about 1500 light-years across, centered on Sagittarius A, a bright radio source that contains the smaller Sagittarius A*. Much of the radio emission comes from hot gas heated either by clusters of hot stars (the stars themselves do not produce radio emission and can't be seen in the image) or by supernova blast waves. Most of the hollow circles visible on the radio image are supernova remnants. The other main source of radio emission is from electrons moving at high speed in regions with strong magnetic fields. The bright thin arcs and "threads" on the figure show us where this type of emission is produced.

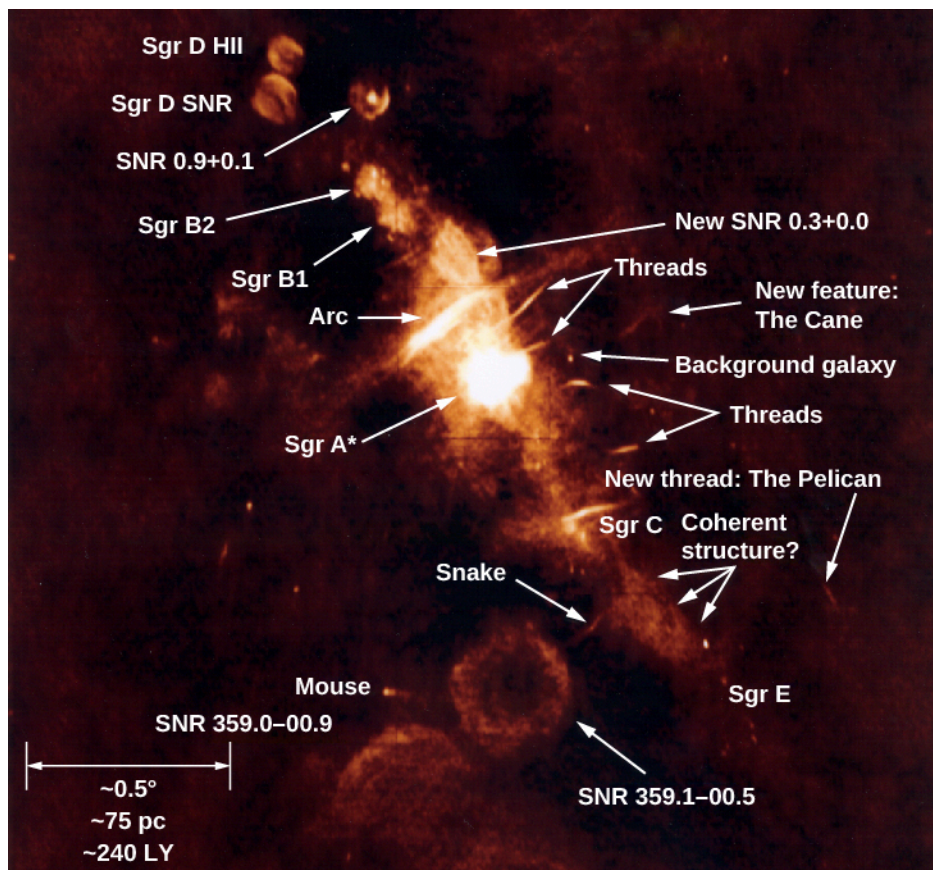


Figure 25.14 Radio Image of Galactic Center Region. This radio map of the center of the Galaxy (at a wavelength of 90 centimeters) was constructed from data obtained with the Very Large Array (VLA) of radio telescopes in Socorro, New Mexico. Brighter regions are more intense in radio waves. The galactic center is inside the region labeled Sagittarius A. Sagittarius B1 and B2 are regions of active star formation. Many filaments or threadlike features are seen, as well as a number of shells (labeled SNR), which are supernova remnants. The scale bar at the bottom left is about 240 light-years long. Notice that radio astronomers also give fanciful animal names to some of the structures, much as visible-light nebulae are sometimes given the names of animals they resemble. (credit: modification of work by N. E. Kassim, D. S. Briggs, T. J. W. Lazio, T. N. LaRosa, and J. Imamura (NRL/RSD))

Now let's focus in on the central region using a more energetic form of electromagnetic radiation. **Figure 25.15** shows the X-ray emission from a smaller region 400 light-years wide and 900 light-years across centered in Sagittarius A*. Seen in this picture are hundreds of hot white dwarfs, neutron stars, and stellar black holes with accretion disks glowing with X-rays. The diffuse haze in the picture is emission from gas that lies among the stars and is at a temperature of 10 million K.

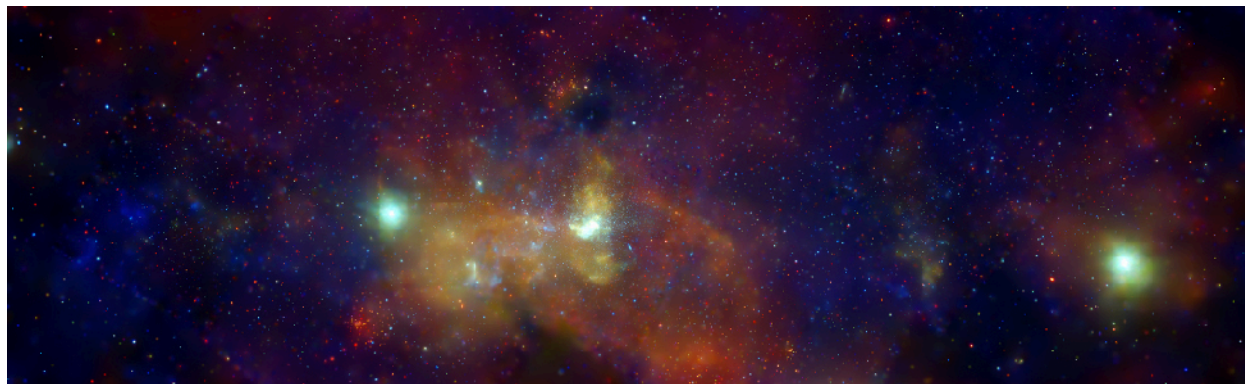


Figure 25.15 Galactic Center in X-Rays. This artificial-color mosaic of 30 images taken with the Chandra X-ray satellite shows a region 400×900 light-years in extent and centered on Sagittarius A*, the bright white source in the center of the picture. The X-ray-emitting point sources are white dwarfs, neutron stars, and stellar black holes. The diffuse "haze" is emission from gas at a temperature of 10 million K. This hot gas is flowing away from the center out into the rest of the Galaxy. The colors indicate X-ray energy bands: red (low energy), green (medium energy), and blue (high energy). (credit: modification of work by NASA/CXC/UMass/D. Wang et al.)

As we approach the center of the Galaxy, we find the supermassive black hole Sagittarius A*. There are also thousands of stars within a parsec of Sagittarius A*. Most of these are old, reddish main-sequence stars. But there are also about a hundred hot OB stars that must have formed within the last few million years. There is as yet no good explanation for how stars could have formed recently so close to a supermassive black hole. Perhaps they formed in a dense cluster of stars that was originally at a larger distance from the black hole and subsequently migrated closer.

There is currently no star formation at the galactic center, but there is lots of dust and molecular gas that is revolving around the black hole, along with some ionized gas streamers that are heated by the hot stars. **Figure 25.16** is a radio map that shows these gas streamers.

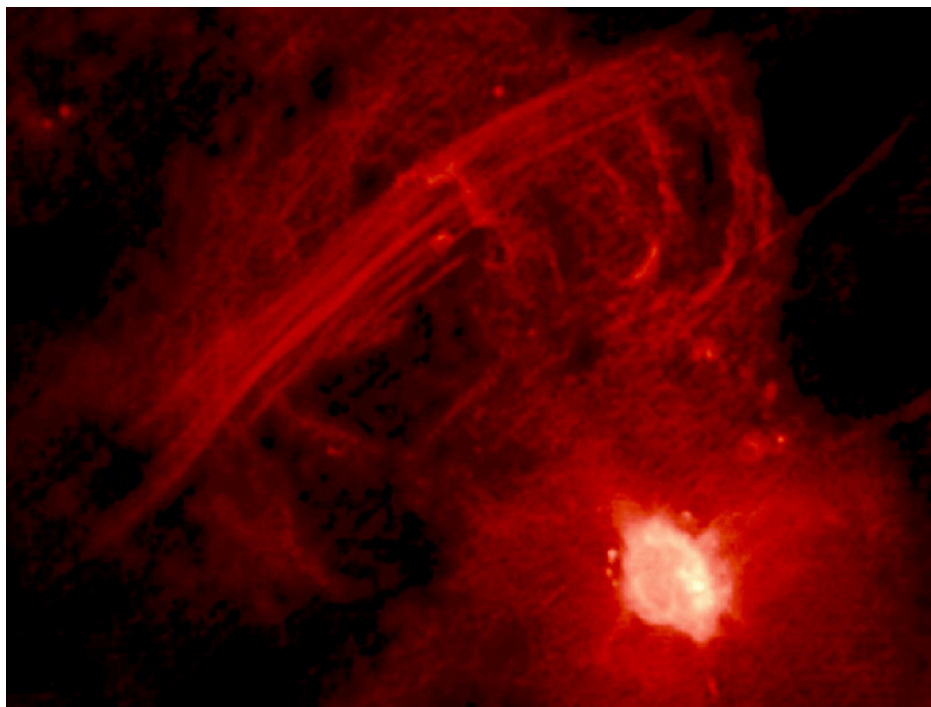


Figure 25.16 Sagittarius A. This image, taken with the Very Large Array of radio telescopes, shows the radio emission from hot, ionized gas in the center of the Milky Way. The lines slanting across the top of the image are gas streamers. Sagittarius A* is the bright spot in the lower right. (credit: modification of work by Farhad Zadeh et al. (Northwestern), VLA, NRAO)

Finding the Heart of the Galaxy

Just what is Sagittarius A*, which lies right at the center of our Galaxy? To establish that there really is a black hole there, we must show that there is a very large amount of mass crammed into a very tiny volume. As we saw in [Black Holes and Curved Spacetime](#), proving that a black hole exists is a challenge because the black hole itself emits no radiation. What astronomers must do is prove that a black hole is the only possible explanation for our observations—that a small region contains far more mass than could be accounted for by a very dense cluster of stars or something else made of ordinary matter.

To put some numbers with this discussion, the radius of the event horizon of a *galactic black hole* with a mass of about 4 million M_{Sun} would be only about 17 times the size of the Sun—the equivalent of a single red giant star. The corresponding density within this region of space would be much higher than that of any star cluster or any other ordinary astronomical object. Therefore, we must measure both the diameter of Sagittarius A* and its mass. Both radio and infrared observations are required to give us the necessary evidence.

First, let's look at how the mass can be measured. If we zero in on the inner few light-days of the Galaxy with an infrared telescope equipped with adaptive optics, we see a region crowded with individual stars ([Figure 25.17](#)). These stars have now been observed for almost two decades, and astronomers have detected their rapid orbital motions around the very center of the Galaxy.

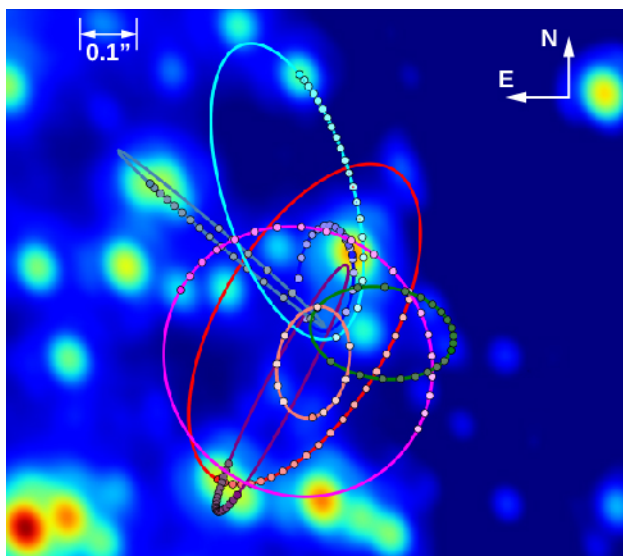


Figure 25.17 Near-Infrared View of the Galactic Center. This image shows the inner 1 arcsecond, or 0.13 light-year, at the center of the Galaxy, as observed with the giant Keck Telescope. Tracks of the orbiting stars measured from 1995 to 2014 have been added to this “snapshot.” The stars are moving around the center very fast, and their tracks are all consistent with a single massive “gravitator” that resides in the very center of this image. (credit: modification of work by Andrea Ghez, UCLA Galactic Center Group, W.M. Keck Observatory Laser Team)

LINK TO LEARNING



Check out an [animated version \(https://openstaxcollege.org/l/30anifiginfgal\)](https://openstaxcollege.org/l/30anifiginfgal) of [Figure 25.17](#), showing the motion of the stars over the years.

If we combine observations of their periods and the size of their orbits with Kepler's third law, we can estimate the mass of the object that keeps them in their orbits. One of the stars has been observed for its full orbit of 15.6 years. Its closest approach takes it to a distance of only 124 AU or about 17 light-hours from the black hole.

This orbit, when combined with observations of other stars close to the galactic center, indicates that a mass of 4.6 million M_{Sun} must be concentrated inside the orbit—that is, within 17 light-hours of the center of the Galaxy.

Even tighter limits on the size of the concentration of mass at the center of the Galaxy come from radio astronomy, which provided the first clue that a black hole might lie at the center of the Galaxy. As matter spirals inward toward the event horizon of a black hole, it is heated in a whirling *accretion disk* and produces radio radiation. (Such accretion disks were explained in [Black Holes and Curved Spacetime](#).) Measurements of the size of the accretion disk with the Very Long Baseline Array, which provides very high spatial resolution, show that the diameter of the radio source Sagittarius A* is no larger than about 0.3 AU, or about the size of Mercury's orbit. (In light units, that's only 2.5 light-*minutes*!)

The observations thus show that 4.6 million solar masses are crammed into a volume that has a diameter that is no larger than the orbit of Mercury. If this were anything other than a supermassive black hole—low-mass stars that emit very little light or neutron stars or a very large number of small black holes—calculations show that these objects would be so densely packed that they would collapse to a single black hole within a hundred thousand years. That is a very short time compared with the age of the Galaxy, which probably began forming more than 13 billion years ago. Since it seems very unlikely that that we would have caught such a complex cluster of objects just before it collapsed, the evidence for a supermassive black hole at the center of the Galaxy is convincing indeed.

Finding the Source

Where did our galactic black hole come from? The origin of supermassive black holes in galaxies like ours is currently an active field of research. One possibility is that a large cloud of gas near the center of the Milky Way collapsed directly to form a black hole. Since we find large black holes at the centers of most other large galaxies (see [Active Galaxies, Quasars, and Supermassive Black Holes](#))—even ones that are very young—this collapse probably would have taken place when the Milky Way was just beginning to take shape. The initial mass of this black hole might have been only a few tens of solar masses. Another way it could have started is that a massive star might have exploded to leave behind a seed black hole, or a dense cluster of stars might have collapsed into a black hole.

Once a black hole exists at the center of a galaxy, it can grow over the next several billion years by devouring nearby stars and gas clouds in the crowded central regions. It can also grow by merging with other black holes.

It appears that the monster black hole at the center of our Galaxy is not finished “eating.” At the present time, we observe clouds of gas and dust falling into the galactic center at the rate of about 1 M_{Sun} per thousand years. Stars are also on the black hole's menu. The density of stars near the galactic center is high enough that we would expect a star to pass near the black hole and be swallowed by it every ten thousand years or so. As this happens, some of the energy of infall is released as radiation. As a result, the center of the Galaxy might flare up and even briefly outshine all the stars in the Milky Way. Other objects might also venture too close to the black hole and be pulled in. How great a flare we observe would depend on the mass of the object falling in.

In 2013, the Chandra X-ray satellite detected a flare from the center of our Galaxy that was 400 times brighter than the usual output from Sagittarius A*. A year later, a second flare, only half as bright, was also detected. This is much less energy than swallowing a whole star would produce. There are two theories to account for the flares. First, an asteroid might have ventured too close to the black hole and been heated to a very high temperature before being swallowed up. Alternatively, the flares might have involved interactions of the magnetic fields near the galactic center in a process similar to the one described for solar flares (see [The Sun: A Garden-Variety Star](#)). Astronomers continue to monitor the galactic center area for flares or other activity. Although the monster in the center of the Galaxy is not close enough to us to represent any danger, we still want to keep our eyes on it.

VOYAGERS IN ASTRONOMY



Andrea Ghez

A lover of puzzles, Andrea Ghez has been pursuing one of the greatest mysteries in astronomy: what strange entity lurks within the center of our Milky Way Galaxy?



Figure 25.18 Andrea Ghez. Research by Ghez and her team has helped shape our understanding of supermassive black holes. (credit: modification of work by John D. and Catherine T. MacArthur Foundation)

As a child living in Chicago during the late 1960s, Andrea Ghez ([Figure 25.18](#)) was fascinated by the Apollo Moon landings. But she was also drawn to ballet and to solving all sorts of puzzles. By high school, she had lost the ballet bug in favor of competing in field hockey, playing the flute, and digging deeper into academics. Her undergraduate years at MIT were punctuated by a number of changes in her major—from mathematics to chemistry, mechanical engineering, aerospace engineering, and finally physics—where she felt her options were most open. As a physics major, she became involved in astronomical research under the guidance of one of her instructors. Once she got to do some actual observing at Kitt Peak National Observatory in Arizona, and later at Cerro Tololo Inter-American Observatory in Chile, Ghez had found her calling.

Pursuing her graduate studies at Caltech, she stuck with physics but oriented her efforts toward observational astrophysics, an area where Caltech had access to cutting-edge facilities. Though initially attracted to studying the black holes that were suspected of dwelling inside most massive galaxies, Ghez ended up spending most of her graduate study and later postdoctoral research at the University of Arizona studying stars in formation. By taking very high-resolution (detailed) imaging of regions where new stars are born, she discovered that most stars form as members of binary systems. As technologies advanced, she was able to track the orbits danced by these stellar pairings and thereby could ascertain their respective masses.

Now an astronomy professor at UCLA, Ghez has since used similar high-resolution imaging techniques to study the orbits of stars in the innermost core of the Milky Way. These orbits take years to delineate, so Ghez and her science team have logged more than 20 years of taking super-resolution infrared images with the giant Keck telescopes in Hawaii. Based on the resulting stellar orbits, the UCLA Galactic Center Group has settled (as we saw) on a gravitational solution that requires the presence of a supermassive black hole with a mass equivalent to 4.6 million Suns—all nestled within a space smaller than that

occupied by our solar system. Ghez's achievements have been recognized with one of the "genius" awards given by the MacArthur Foundation. More recently, her team discovered glowing clouds of warm ionized gas that co-orbit with the stars but may be more vulnerable to the disruptive effects of the central black hole. By monitoring these clouds, the team hopes to better understand the evolution of supermassive black holes and their immediate environs. They also hope to test Einstein's theory of general relativity by carefully scrutinizing the orbits of stars that careen closest to the intensely gravitating black hole.

Besides her pioneering work as an astronomer, Ghez competes as a master swimmer, enjoys family life as a mother of two children, and actively encourages other women to pursue scientific careers.

25.5 STELLAR POPULATIONS IN THE GALAXY

Learning Objectives

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

- › Distinguish between population I and population II stars according to their locations, motions, heavy-element abundances, and ages
- › Explain why the oldest stars in the Galaxy are poor in elements heavier than hydrogen and helium, while stars like the Sun and even younger stars are typically richer in these heavy elements

In the first section of this chapter, we described the thin disk, thick disk, and stellar halo. Look back at [Table 25.1](#) and note some of the patterns. Young stars lie in the thin disk, are rich in metals, and orbit the Galaxy's center at high speed. The stars in the halo are old, have low abundances of elements heavier than hydrogen and helium, and have highly elliptical orbits randomly oriented in direction (see [Figure 25.19](#)). Halo stars can plunge through the disk and central bulge, but they spend most of their time far above or below the plane of the Galaxy. The stars in the thick disk are intermediate between these two extremes. Let's first see why age and heavier-element abundance are correlated and then see what these correlations tell us about the origin of our Galaxy.

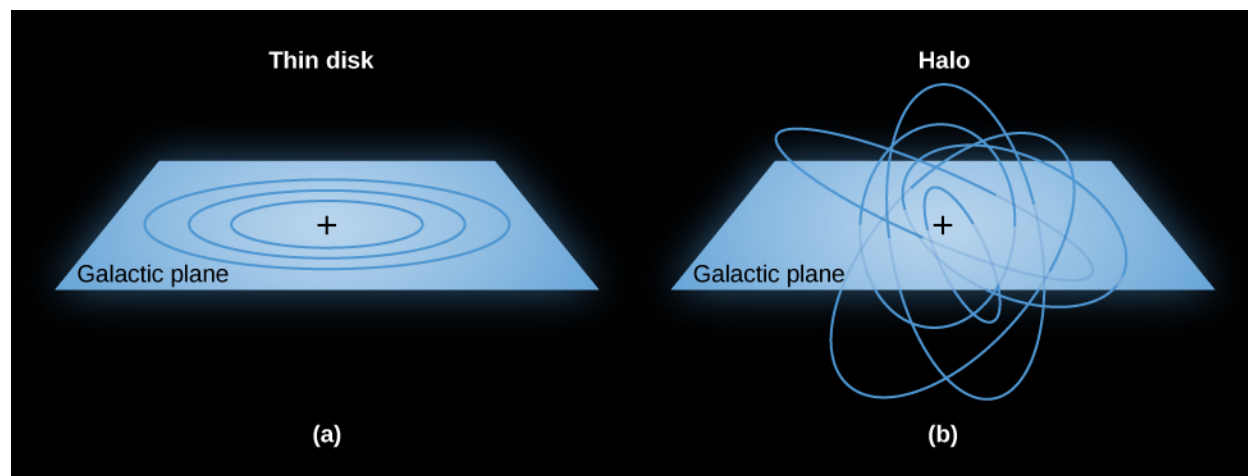


Figure 25.19 How Objects Orbit the Galaxy. (a) In this image, you see stars in the thin disk of our Galaxy in nearly circular orbits. (b) In this image, you see the motion of stars in the Galaxy's halo in randomly oriented and elliptical orbits.