23 THE MILKY WAY GALAXY

A Grand Design

(Background) The varying interrelationships among the many components of matter in our Milky Way Galaxy comprise a sort of "galactic ecosystem." Its evolutionary balance may be as complex as that of life in a tidal pool or a tropical rainforest. Here, stars abound throughout the Lagoon Nebula, a rich stellar nursery about 1200 pc from Earth.

(Inset A) An emission nebula, the North American Nebula, glowing amidst a field of stars, its red color produced by the emission of light from vast clouds of hydrogen atoms.
(Inset B) An open cluster, the Jewel Box, containing many young, blue stars.
(Inset C) A typical globular cluster, 47 Tucanae. This true-color image reveals its dominant member stars to be elderly red giants.
(Inset D) A true-color *Hubble* image of part of the Cygnus Loop—a supernova remnant, the remains of a colossal stellar explosion that occurred about 15,000 years ago.

LEARNING GOALS

Studying this chapter will enable you to:

1 Describe the overall structure of the Milky Way Galaxy and specify how the various regions differ from one another.

2 Explain the importance of variable stars in determining the size and shape of our Galaxy.

3 Describe the orbital paths of stars in different regions of the Galaxy and explain how these motions are accounted for by our understanding of how the Galaxy formed.

4 Discuss some possible explanations for the existence of the spiral arms observed in our own and many other galaxies.

5 Explain what studies of galactic rotation reveal about the size and mass of our Galaxy and discuss the possible nature of dark matter.

6 Describe some of the phenomena observed at the center of our Galaxy.

L*ooking up on a dark, clear night, we are struck by two aspects of the night sky. The first is a fuzzy band of light—the Milky Way—that stretches across the heavens. From the Northern Hemisphere this band is most easily visible in the summertime, arcing high above the horizon. Its full extent forms a great circle that encompasses the entire celestial sphere. Away from that glowing band, however, our second impression is that the nighttime sky seems more or less the same in all directions. Bunches of stars cluster here and there, but overall, apart from the band of the Milky Way, the evening sky looks pretty uniform. Yet this is only a local impression. Ours is a rather provincial view. When we consider much larger volumes of space, on scales far, far greater than the distances between neighboring stars, a new level of organization becomes apparent as the large-scale structure of the Milky Way Galaxy is revealed.*

23.1 Our Parent Galaxy

1 A **galaxy** is a gargantuan collection of stellar and interstellar matter—stars, gas, dust, neutron stars, black holes—isolated in space and held together by its own gravity. Astronomers are aware of literally millions of galaxies beyond our own. The particular galaxy we happen to inhabit is known as the **Milky Way Galaxy**, or just *the Galaxy*, with a capital *G*.

Our Sun lies in a part of the Galaxy known as the **Galactic disk**—an immense, circular, flattened region containing most of our Galaxy's luminous stars and interstellar matter (and virtually everything we have studied so far in this book). We do not need sophisticated astronomical equipment to verify this statement. Our own unaided eyes will suffice. Figure 23.1 illustrates how, viewed from within, the Galactic disk appears as a band of light stretching across our night sky, a band known as the *Milky Way*. As indicated in the figure, if we look in a direction away from the Galactic disk (red arrows), relatively few stars lie in our field of view. However, if our line of sight happens to lie within the disk (white and blue arrows), we see so many stars that their light merges into a continuous blur.

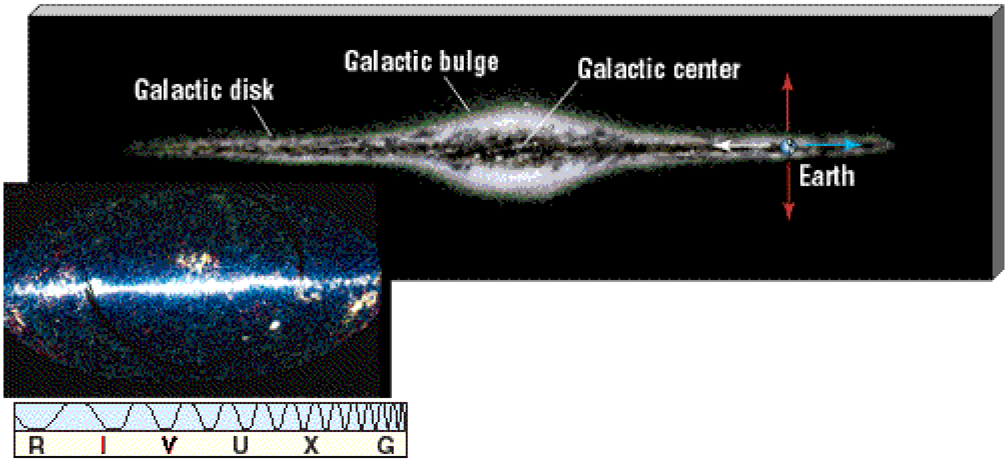

Figure 23.1 *Gazing from Earth toward the Galactic center (white arrow), in this artist's conception, we see myriad stars stacked up within the thin band of light known as the Milky Way. Looking in the opposite direction (blue arrow), we still see the Milky Way band, but now it is fainter because our position is far from the Galactic center, with the result that we see more stars when looking toward the center than when looking in the opposite direction. Looking perpendicular to the disk (red arrows), we see far fewer stars. The inset is an enhanced infrared satellite view of the sky all around us; the white band is the disk of our Milky Way Galaxy, which can be seen with the naked eye from very dark locations on Earth.*

Paradoxically, although we can study individual stars and interstellar clouds near the Sun in great detail, our location within the Galactic disk makes deciphering our Galaxy's large-scale structure from Earth a very difficult task—a little like trying to unravel the layout of paths, bushes, and trees in a city park without being able to leave one particular park bench. In some directions the interpretation of what we see is ambiguous and inconclusive. In others, foreground objects completely obscure our view of what lies beyond, but we cannot move around them to get a better look. As a result, astronomers who study the Milky Way Galaxy are often guided in their efforts by comparisons with more distant, but much more easily observable, systems.

Figures 23.2 and 23.3 show three galaxies thought to resemble our own in overall structure. Figure 23.2 is the Andromeda Galaxy, the nearest major galaxy to the Milky Way Galaxy, lying about 900 kpc (nearly 3 million light years) away. Andromeda's apparent elongated shape is a consequence of the angle at which we happen to view it. In fact, this galaxy, like our own, consists of a circular galactic disk of matter that fattens to a **galactic bulge** at the center. The disk and bulge are embedded in a roughly spherical ball of faint old stars known as the **galactic halo**. These three basic galactic regions are indicated on the figure (the halo stars are so faint that they cannot be discerned here; see Figure 23.10). Figure 23.3(a) and (b) shows views of two other galaxies—one seen face-on, the other edge-on—that illustrate these points more clearly.

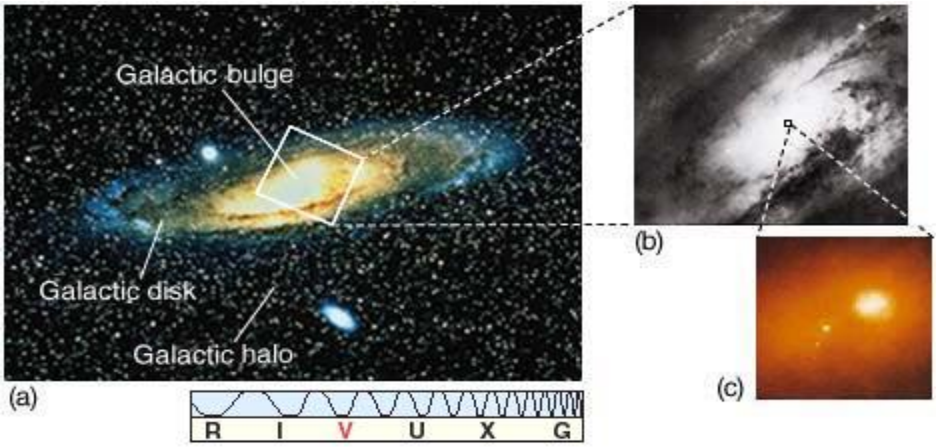

Figure 23.2 *(a) The Andromeda Galaxy probably resembles fairly closely the overall layout of our own Milky Way Galaxy. The disk and bulge are clearly visible in this image, which is about 30,000 pc across. The faint halo stars cannot be seen. The white stars sprinkled all across this image are not part of Andromeda's halo; they are foreground stars in our own Galaxy, lying in the same part of the sky as Andromeda, but about a thousand times closer. (b)*

More detail within the inner parts of the galaxy. (c) The galaxy's peculiar—and still unexplained—double core; this inset covers a region only 15 pc across.

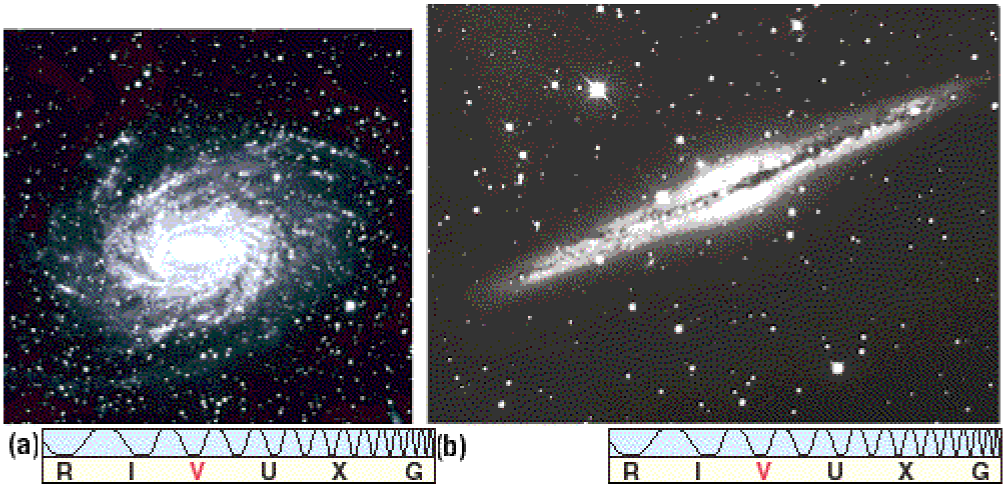

Figure 23.3 *(a) This galaxy, catalogued as NGC, and seen nearly face-on, is somewhat similar in its overall structure to our own Milky Way Galaxy and Andromeda. (b) The galaxy NGC 891 happens to be oriented in such a way that we see it edge-on, allowing us to see clearly its disk and central bulge.*

23.2 Measuring the Milky Way

Before the twentieth century, astronomers' conception of the cosmos differed markedly from the modern view. The fact that we live in just one of many enormous "islands" of matter separated by even larger tracts of apparently empty space was completely unknown, and the clear distinction between "our Galaxy" and "the universe" did not exist. The twin ideas that (1) the Sun is not at the center of the Galaxy and (2) the Galaxy is not at the center of the universe required both time and hard observational evidence before they gained widespread acceptance.

STAR COUNTS

In the late eighteenth century, long before the distances to any stars were known, the English astronomer William Herschel tried to estimate the size and shape of our Galaxy simply by counting how many stars he could see in different directions in the sky. Assuming that all stars were of about equal brightness, he concluded that the Galaxy was a somewhat flattened, roughly disk-shaped collection of stars lying in the plane of the Milky Way, with the Sun at its *center* (Figure 23.4). Subsequent refinements to this approach led to essentially the same picture; early in the twentieth century some workers went so far as to estimate the dimensions of this "Galaxy" as about 10 kpc in diameter by 2 kpc thick.

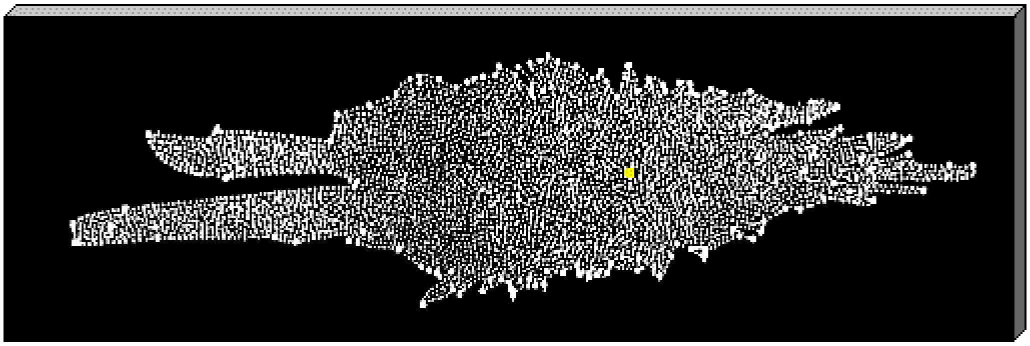

Figure 23.4 *Eighteenth-century English astronomer William Herschel constructed this "map" of the Galaxy by counting the numbers of stars he saw in different directions in the sky. He assumed that all stars were of roughly equal luminosity and, within the confines of the Galaxy, were uniformly distributed in space. Our Sun (marked by the large yellow dot) appears to lie near the center of the distribution, and the long axis of the diagram lies in the plane of the Galactic disk.*

Today the Milky Way Galaxy is known to be several tens of kiloparsecs across, and the Sun lies far from the center. How could the older picture have been so flawed? The answer is that the earlier observations were made in the visible part of the electromagnetic spectrum, and astronomers failed to take into account the (then unknown) absorption of visible light by interstellar gas and dust. ∞(Sec. 18.1) Only in the 1930s did astronomers begin to realize the true extent and importance of the interstellar medium.

Any objects in the Galactic disk that are more than a few kiloparsecs away from us are hidden from our view by the effects of interstellar absorption. The apparent falloff in the density of stars with distance in the plane of the Milky Way is thus not a real thinning of their numbers in space but simply a consequence of the murky environment in the Galactic disk. The long "fingers" in Herschel's map are directions in which the obscuration happens to be a little less severe than in others. However, because some obscuration occurs in all directions in the disk, the falloff is roughly similar no matter which way we look, and so the Sun appears to be more or less at the center. The horizontal extent of Figure 23.4 corresponds approximately to the span of the blue and white arrows in Figure 23.1.

In contrast, radiation coming to us from above or below the plane of the Galaxy, where there is less gas and dust along the line of sight, arrives on Earth relatively unscathed. There is still some patchy obscuration, but the Sun happens to lie in a location where the view out of the disk is largely unimpeded by nearby interstellar clouds.

SPIRAL NEBULAE AND GLOBULAR CLUSTERS

We have just seen how astronomers' attempts to probe the Galactic disk by optical means are frustrated by the effects of the interstellar medium, whereas looking in other directions, out of the Milky Way plane, we can see to much greater distances. During the first quarter of the twentieth century, studies of the large-scale structure of our Galaxy focused on two particularly important classes of objects, both found mainly away from the Milky Way. The first are *globular clusters*, those tightly bound swarms of old, reddish stars we first met in Chapter 17. ∞(Sec. 17.10) About 140 are now known. The second were known at the time as *spiral nebulae*. Examples are shown in Figures 23.2(a) and 23.3(a). We know them today as **spiral galaxies**, comparable in size to our own.

Early twentieth-century astronomers had no means of determining the distances to any of these objects. They are far too distant to have any observable parallax and, with the technology of the day, main-sequence stars (after the discovery of the main sequence in 1911) could not be clearly identified and measured. For these reasons neither of the techniques discussed in Chapter 17 was applicable. ∞(Sec. 17.1) ∞(Sec. 17.8) As a result, even the most basic properties—size, mass, and stellar and interstellar content—of globular clusters and spiral nebulae were unknown. It was assumed that the globular clusters lay within our own Galaxy, which was thought at the time to be relatively small (using the size estimates, just mentioned). The locations of the spiral nebulae were much less clear.

Knowing the distance to an object is vitally important to understanding its true nature. As an example, consider again the Andromeda "nebula" (Figure 23.2). In the late nineteenth century, when improved telescopes and photographic techniques allowed astronomers to obtain images showing detail comparable to Figure 23.(a), the newly released photographs caused great excitement among astronomers, who thought they were seeing the formation of a star from a swirling gaseous disk! Comparing Figure 23.2(a) with the figures in Chapter 15 (see especially Figure 15.1b), we can perhaps understand how such a mistake could be made—*if* we believed we were looking at a relatively close, star-sized object. Far from demonstrating that Andromeda was distant and large, the new observations seemed to confirm that it was just a small part of our own Galaxy.

Further observations soon made it clear that Andromeda is not a star-forming region. Andromeda's parallax is too small to measure, indicating that it must be at least several hundred parsecs from Earth, and, even at 100 pc—which we now know is vastly less than Andromeda's true distance—an object the size of the solar nebula would be impossible to resolve and simply would not look like Figure 23.2(a). (For another, much more recent example of how distance measurements affect our theoretical understanding of observational data, see ∞ Section 22.3.)

During the first three decades of the twentieth century, both the size of our Galaxy and the distances to the spiral nebulae were hotly debated in astronomical circles. One school of thought maintained that the spiral nebulae were relatively small systems contained within our Galaxy. Other astronomers held that the spirals were much larger objects, lying far outside the Milky Way Galaxy and comparable to it in size. However, with no firm distance information, both arguments were quite inconclusive. Only with the discovery of a new distance-measurement technique—which we discuss next—was the issue finally settled in favor of the latter view. However, in the process, astronomers' conception of our own Galaxy changed radically and forever.

A NEW YARDSTICK

2 An important by-product of the laborious effort to catalog stars around the turn of the twentieth century was the systematic study of **variable stars**. These are stars whose luminosity changes with time—some quite erratically, others more regularly. Only a small fraction of stars fall into this category, but those that do are of great astronomical significance.

We encountered several examples of variable stars in earlier chapters. Often, the variability is the result of membership in a binary system. Eclipsing binaries, novae, and Type I supernovae are examples. Novae and supernovae collectively are called *cataclysmic variables* because of their sudden, large changes in brightness. In other instances, however, the variability is a basic trait of a star and is not dependent on its being a part of a binary system. We call such a star an *intrinsic variable.*

A particularly important class of intrinsic variables is the class known as **pulsating variable stars**,* which vary cyclically in luminosity in very characteristic ways. Two types of pulsating variable stars that have played central roles in revealing both the true extent of our Galaxy and the distances to our galactic neighbors are the **RR Lyrae** and **Cepheid variables**. Following long-standing astronomical practice, the names come from the first star of each class to be discovered—in this case the variable star labeled RR in the constellation Lyra and the variable star Delta Cephei, the fourth brightest star in the constellation Cepheus, respectively.

* *(note that these stars have nothing whatsoever to do with pulsars.)*

RR Lyrae and Cepheid variable stars are recognizable by the characteristic shapes of their light curves. RR Lyrae stars all pulsate in essentially similar ways (Figure 23.5a), with only small differences in period between one RR Lyrae variable and another. Observed periods range from about 0.5 to 1 day. Cepheid variables also pulsate in distinctive ways (the regular "sawtooth" pattern in Figure 23.5b), but different Cepheids can have very different pulsation periods, ranging from about 1 to 100 days. The period of any given RR Lyrae or Cepheid variable is, to high accuracy, the same from one cycle to the next. The key point is that pulsating variable stars can be recognized and identified *just by observing the variations in the light they emit.*

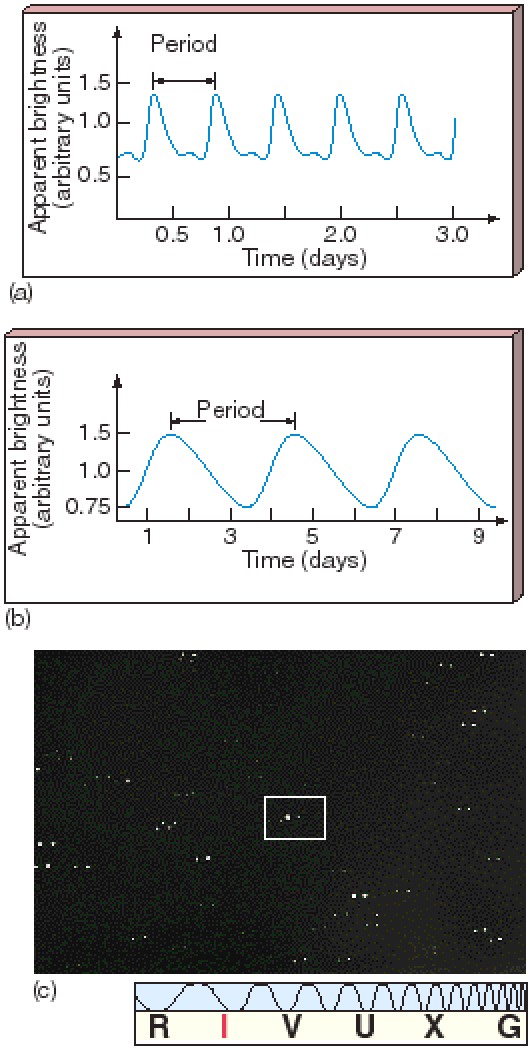

Figure 23.5 *(a) Light curve of the pulsating variable star RR Lyrae. All RR Lyrae-type variables have essentially similar light curves, with periods of less than a day. (b) The light curve of a Cepheid variable star called WW Cygni, having a period of several days. (c) This Cepheid is shown here (boxed) on successive nights, near its maximum and minimum brightness; two photos, one from each night were superimposed and then slightly displaced.*

Why do Cepheids and RR Lyrae variables pulsate? The basic mechanism was first suggested by the British astrophysicist Sir Arthur Eddington in 1941. The structure of any star is determined in large part by how easily radiation can travel from the core to the photosphere—that is, by the *opacity* of the interior, the degree to which the gas hinders the passage of light through it. If the opacity rises, the radiation becomes trapped, the internal pressure increases, and the star "puffs up." If the opacity falls, radiation can escape more easily, and the star shrinks. According to theory, under certain circumstances a star can become unbalanced and enter a state in which the flow of radiation causes the opacity first to rise—making the star expand, cool, and diminish in luminosity—and then to fall, leading to the pulsations we observe.

Thus, pulsating variable stars are normal stars experiencing a brief period of instability as a natural part of stellar evolution. The conditions necessary to cause pulsations are not found in main-sequence stars; they occur in evolved post—main-sequence stars as they pass through a region of the Hertzsprung—Russell diagram known as the *instability strip* (Figure 23.6). When a star's temperature and luminosity place it in this strip, the star becomes internally unstable, and both its temperature and its radius vary in a regular way, causing the pulsations we observe: as the star brightens, its surface becomes hotter and its radius shrinks; as its luminosity decreases, the star expands and cools. As we learned in Chapter 20, high-mass stars evolve across the upper part of the H—R diagram; when their evolutionary tracks take them into the instability strip, they become Cepheid variables. ∞(Sec. 20.4) RR Lyrae variables are low-mass horizontal-branch stars that lie within the lower portion of the instability strip. (Sec. 20.2)

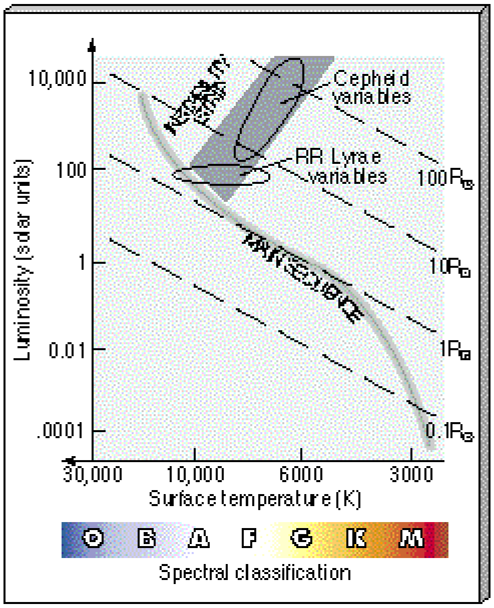

Figure 23.6 *Pulsating variable stars are found in the instability strip of the H—R diagram. As a high-mass star evolves through the strip it becomes a Cepheid variable. Low-mass horizontal-branch stars in the instability strip are RR Lyrae variables.*

The importance of these stars to Galactic astronomy lies in the fact that once we recognize a star as being of the RR Lyrae or Cepheid type, we can infer its luminosity, and that in turn allows us to measure its distance. The distance calculation is precisely the same as presented in Chapter 17 during our discussion of spectroscopic parallax. ∞(Sec. 17.8) Comparing the star's (known) luminosity with its (observed) apparent brightness yields an estimate of its distance, by the inverse-square law: ∞(Sec. 17.4)

$$\text{apparent brightness} \propto \frac{\text{luminosity}}{\text{distance}^2}$$

In this way astronomers can use pulsating variables as a means of determining distances, both within our own Galaxy and far beyond.

How do we infer a variable star's luminosity? For RR Lyrae stars, this is simple. All such stars have basically the same luminosity (averaged over a complete pulsation cycle)—about 100 times that of the Sun—so once a variable star is recognized as being of the RR Lyrae type, its luminosity is immediately known. For Cepheids, we make use of a close correlation between average luminosity and pulsation period, discovered in 1908 by Henrietta Leavitt of Harvard University (see *Interlude 23-1*) and known simply as the **period-luminosity relationship.** Cepheids that vary slowly—that is, have long periods—have large luminosities; conversely, short-period Cepheids have low luminosities.

Figure 23.7 illustrates the period—luminosity relationship for Cepheids found within a thousand parsecs or so of Earth. Astronomers can plot such a diagram for relatively nearby stars because they can measure the distances using stellar or spectroscopic parallax. Once distances are known, the luminosities of those stars can be calculated. We know of no exceptions to the period—luminosity relationship, and it is consistent with theoretical calculations of pulsations in evolved stars. Consequently, we assume that it holds for all Cepheids, near and far. Thus, a simple measurement of a Cepheid variable's pulsation period immediately tells us its luminosity—we just read it off the plot in Figure 23.7. (The roughly constant luminosities of the RR Lyrae variables are also indicated in the figure.)

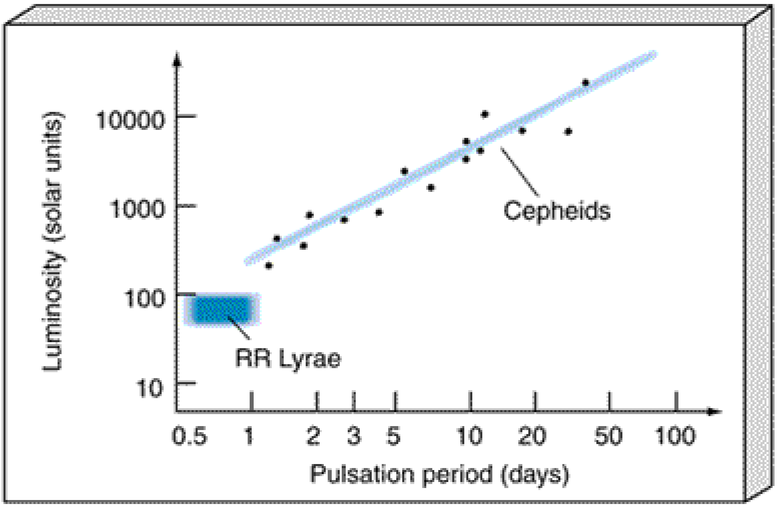

Figure 23.7 *A plot of average absolute brightness (that is, luminosity) versus pulsation period for a group of Cepheid variable stars. The two properties are quite tightly correlated. The pulsation periods of some RR Lyrae variables are also shown.*

This distance-measurement technique works well provided the variable star can be clearly identified and its pulsation period measured. With Cepheids, this method allows astronomers to estimate distances out to about 15 million parsecs, enough to take us all the way to the nearest galaxies. The less luminous RR Lyrae stars are not so easily seen as Cepheids, so their useful range is not as great. However, they are much more common so, within their limited range, they are actually more useful than Cepheids.

Figure 23.8 extends our cosmic distance ladder, begun in Chapter 2 with radar ranging in the solar system and expanded in Chapter 17 to include stellar and spectroscopic parallax, by adding variable stars as a fourth method of determining distance. Note that because the period—luminosity relationship is calibrated using nearby stars, this latest rung inherits any and all uncertainties and errors present in the lower levels. Uncertainties also arise from the "scatter" shown in Figure 23.7. Although the overall connection between period and luminosity is unmistakable, the individual data points do not quite lie on a straight line. Instead, a range of possible luminosities corresponds to any measured period.

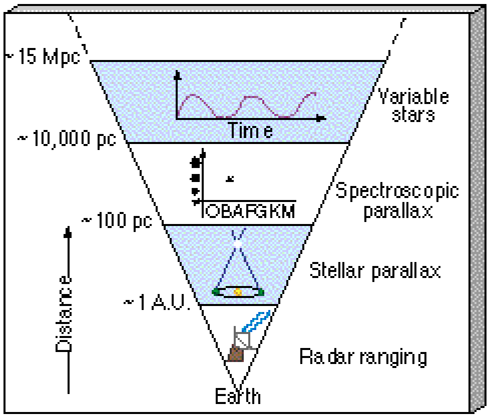

Figure 23.8 *Application of the period—luminosity relationship for Cepheid variable stars allows us to determine distances out to about 15 Mpc with reasonable accuracy.*
Cepheid Star in Distant Galaxy

THE SIZE AND SHAPE OF OUR GALAXY

Many RR Lyrae variables are found in globular clusters. Early in the twentieth century the American astronomer Harlow Shapley used observations of RR Lyrae stars to make two very important discoveries about the Galactic globular cluster system. First, he showed that most globular clusters reside at great distances—many thousands of parsecs—from the Sun. Second, by measuring the direction and distance of each cluster, he was able to determine their three-dimensional distribution in space. In this way Shapley demonstrated that the globular clusters map out a truly gigantic, and roughly *spherical*, volume of space, about 30 kpc across.* However, the center of the distribution lies nowhere near our Sun. It is located nearly 8 kpc away from us, in the direction of the constellation Sagittarius.

** (The Galactic globular cluster system and the Galactic halo of which it is a part are somewhat flattened in the direction perpendicular to the disk, but the degree of flattening is quite uncertain. The halo is certainly much less flattened than the disk, however.)*

In a brilliant intellectual leap, Shapley realized that the distribution of globular clusters maps out the true extent of stars in the Milky Way Galaxy—the region that we now call the Galactic halo. (Since Shapley's time astronomers have identified many individual halo stars that do not belong to any globular cluster.) The hub of this vast collection of matter, 8 kpc from the Sun, is the **Galactic center**. As illustrated in Figure 23.9, we live in the suburbs of this huge ensemble, in the Galactic disk—the thin sheet of young stars, gas, and dust that cuts through the center of the halo.

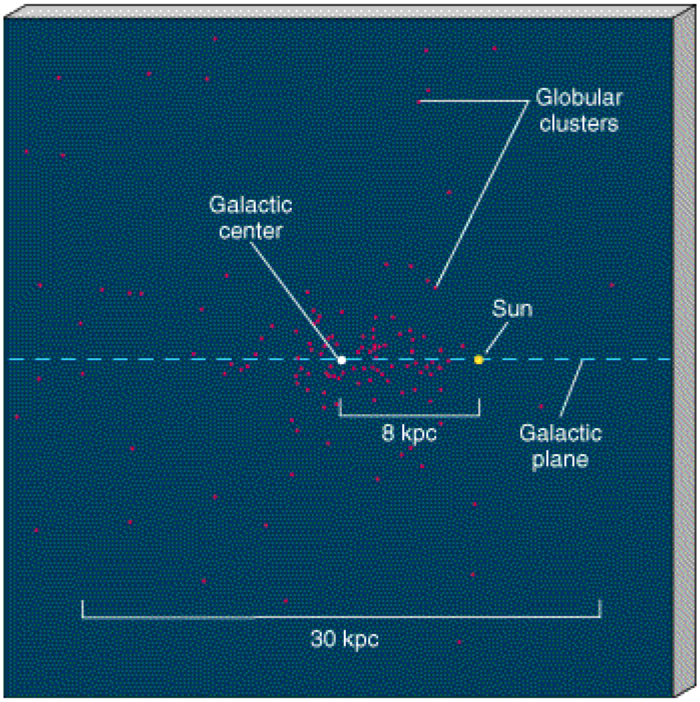

Figure 23.9 *Our Sun does not coincide with the center of the very large collection of globular clusters. Instead, more globular clusters are found in one direction than in any other. The Sun resides closer to the edge of the collection, which measures roughly 30 kpc across. We now know that the globular clusters outline the true distribution of stars in the Galactic halo.*

Shapley's bold interpretation of the globular clusters as defining the overall distribution of stars in our Galaxy was an enormous step forward in human understanding of our place in the universe. Five hundred years ago, Earth was considered the center of all things. Copernicus argued otherwise, demoting our planet to an undistinguished place removed from the center of the solar system. In Shapley's time, as we have just seen, the prevailing view was that our Sun was the center not only of the Galaxy but also of the universe. Shapley showed otherwise. With his observations of globular clusters he simultaneously increased the size of our Galaxy by almost a factor of 10 over earlier estimates and banished our parent Sun to its periphery, virtually overnight!

Curiously, Shapley's dramatic revision of the size of the Milky Way Galaxy and our place in it only strengthened his erroneous opinion that the spiral nebulae were part of our Galaxy and that our Galaxy was essentially the entire universe. He regarded as beyond belief the idea that there could be other structures as large as our Galaxy. Only in the late 1920s was the Copernican principle extended to the Galaxy itself, when American astronomer Edwin Hubble observed Cepheids in the Andromeda Galaxy and finally succeeded in measuring its distance.

23.3 The Large-Scale Structure of Our Galaxy

THE SPATIAL DISTRIBUTION OF STARS

1 Figure 23.10 illustrates the very different spatial distributions of the disk and halo components of the Milky Way Galaxy. As just mentioned, the Sun lies about 8 kpc from the Galactic center. Based on optical, infrared, and radio observations of stars, gas, and dust found within a thousand or so parsecs of the Sun, astronomers estimate that the disk in the vicinity of the Sun is relatively thin—"only" 300 pc thick, or about 1/100 of the Galactic diameter. Don't be fooled, though. Even if you could travel at the speed of light, it would take you 1000 years to traverse the thickness of the Galactic disk. The disk may be thin compared with the Galactic diameter, but it is huge by human standards.

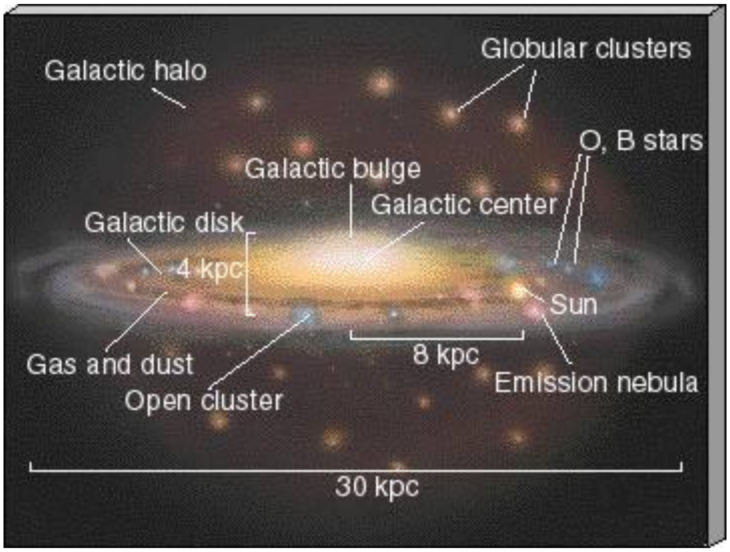

Figure 23.10 *Artist's conception of a (nearly) edge-on view of the Milky Way Galaxy, showing the distributions of young blue stars, open clusters, old red stars, and globular clusters.*

Actually, the thickness of the Galactic disk depends on the kinds of objects measured. Young stars and interstellar gas are more tightly confined to the plane than are stars like the Sun, and solar-type stars in turn are more tightly confined than are older K- and M-type dwarfs. The reason for this is that stars form in interstellar clouds close to the disk plane but then tend to drift out of the disk over time, mainly due to their interactions with other stars and molecular clouds. Thus, as stars age, their abundance above and below the disk plane slowly increases. Note that these considerations do not apply to the Galactic halo, whose ancient stars and globular clusters extend far above and below the Galactic plane. As we will see in a moment, the halo is a remnant of an early stage of our Galaxy's evolution and predates the formation of the disk.

Recently, improved observational techniques have revealed an intermediate category of Galactic stars, midway between the old halo and the younger disk, both in age and in spatial distribution. Consisting of stars with estimated ages in the range of 7—10 billion years, this **thick disk** component of the Milky Way Galaxy measures some 2—3 kpc from top to bottom. Its thickness is also too great to be explained by the slow drift just described. Like the halo, it appears to be a vestige of our Galaxy's distant past.

Also shown in Figure 23.10 is our Galaxy's central bulge, measuring roughly 6 kpc across in the plane of the Galactic disk by 4 kpc perpendicular to the disk plane. Obscuration by interstellar dust makes it difficult to study the detailed structure of the Galactic bulge in optical images of the Milky Way (see, for example, Figure 18.5, which would clearly show a large portion of the bulge were it not for interstellar absorption). However, at longer wavelengths, which are less affected by interstellar matter, a much clearer picture emerges (Figure 23.11; compare with Figure 23.3b). Detailed measurements of the motion of gas and stars in and near the bulge imply that it is football shaped, about half as wide as it is long, with the long axis of the football lying in the Galactic plane.

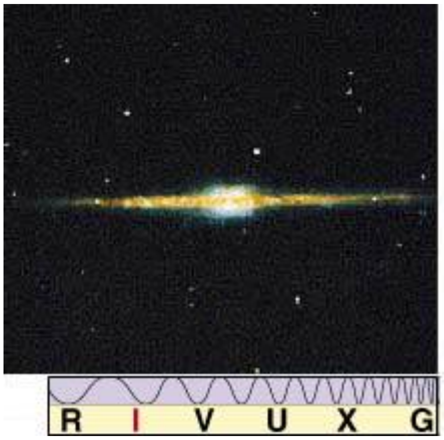

Figure 23.11 *A wide-angle far-infrared image of the disk and bulge of the Milky Way Galaxy, as observed by the Cosmic Background Explorer (COBE) satellite.*

STELLAR POPULATIONS

Aside from their shapes, the three components of the Galaxy—disk, bulge, and halo—have several other properties that distinguish them from one another. First, the halo contains essentially *no* gas or dust—just the opposite of the disk and bulge, in which interstellar matter is common. Second, there are clear differences in both *appearance* and *composition* between disk, bulge, and halo stars. Stars in the Galactic bulge and halo are found to be distinctly *redder* than stars found in the disk. Observations of other spiral galaxies also show this trend—the blue-white tint of the disk and the yellowish coloration of the bulge are evident in Figures 23.2(a) and 23.3(a).

All the bright, blue stars visible in our sky are part of the Galactic disk, as are the young open star clusters and star-forming regions. In contrast, the cooler, redder stars—including those found in the old globular clusters—are more uniformly distributed throughout the disk, bulge, and halo. Galactic disks appear bluish because main-sequence O and B blue supergiants are very much brighter than G, K, and M dwarfs, even though the dwarfs are present in far greater numbers.

The explanation for the marked difference in stellar content between disk and halo is this: whereas the gas-rich Galactic disk is the site of ongoing star formation and so contains stars of all ages, all the stars in the Galactic halo are *old*. The absence of dust and gas in the halo means that no new stars are forming there, and star formation apparently ceased long ago—at least 10 billion years in the past, judging from the types of halo stars we now observe. (Recall from Chapter 20 that most globular clusters are thought to be between 10 and 12 billion years old.) ∞(Sec. 20.5) The gas density is very high in the inner part of the Galactic bulge, making this region the site of vigorous ongoing star formation, and both very old and very young stars mingle there. The bulge's gas-poor outer regions have properties more similar to those of the halo.

Support for this picture comes from studies of the spectra of halo stars, which indicate that these stars are far less abundant in heavy elements (that is, elements heavier than helium) than are nearby stars in the disk. In Chapter 21 we saw how each successive cycle of star formation and evolution enriches the interstellar medium with the products of stellar nucleosynthesis, leading to a steady increase in heavy elements with time. ∞(Sec. 21.5) Thus, the scarcity of these elements in halo stars is consistent with the view that the halo formed long ago.

Astronomers often refer to young disk stars as *Population I* stars and to old halo stars as *Population II* stars. The idea of two stellar "populations" dates from the 1930s, when the differences between disk and halo stars first became clear. The names are something of an oversimplification, as there is actually a continuous variation in stellar ages throughout the Milky Way Galaxy, not a simple division of stars into two distinct "young" and "old" categories. Nevertheless, the terminology is still widely used.

ORBITAL MOTION

3 Now let's turn our attention to the *dynamics* of the Milky Way Galaxy—that is, to the motion of the stars, dust, and gas it contains. Are the internal motions of our Galaxy's members chaotic and random, or are they part of some gigantic "traffic pattern"? The answer depends on our perspective. The motion of stars and clouds we see on small scales (within a few tens of parsecs of the Sun) seems random, but on larger scales (hundreds or thousands of parsecs) the motion is much more orderly.

As we look around the Galactic disk in different directions, a clear pattern of motion emerges (Figure 23.12). Radiation received from stars and interstellar gas clouds in the upper right and the lower left quadrants of Figure 23.12 is generally *blueshifted*. At the same time, the interstellar regions sampled in the upper left quadrant and the lower right quadrant are *redshifted*. In other words, some regions of the Galaxy (in the blueshifted directions) are approaching the Sun, while others (the redshifted ones) are receding from us.

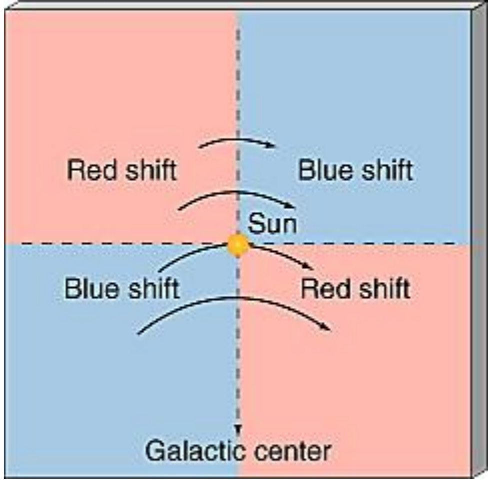

Figure 23.12 *Stars and interstellar clouds in the neighborhood of the Sun show systematic Doppler motions. This information tells us that the disk of the Galaxy is spinning in a well-ordered way. These four Galactic quadrants are drawn (as dashed lines) to intersect at the Sun, not at the Galactic center, because it is from the viewpoint of our own planetary system that the observations are made. The longer the arrow, the greater the angular speed of the disk material. Because the Sun orbits faster than stars and gas at larger radii, we are drawing away from material at top left and gaining on that at top right, resulting in the Doppler shifts indicated. Similarly, stars and gas in the bottom left quadrant are gaining on us, while material at bottom right is pulling away.*

Careful study of the data leads to the conclusion that the entire Galactic disk is *rotating* about the Galactic center. In the vicinity of the Sun, the orbital speed is about 220 km/s. At the Sun's distance of 8 kpc from the Galactic center, material takes about 225 million years—an interval of time sometimes known as 1 *Galactic year*—to complete one circuit. At other distances from the center the rotation period is different—shorter closer to the center, longer at greater distances—that is, the Galactic disk rotates not as a solid object but *differentially*. Similar differential rotation is observed in Andromeda (and, in fact, in all other spiral galaxies).

This picture of orderly circular orbital motion about the Galactic center applies only to the Galactic disk. Stars in the Galactic halo and bulge are not so well behaved. The old globular clusters in the halo and the faint, reddish individual stars in both the halo and the bulge do *not* share the disk's well-defined rotation.

Instead, their orbits are largely random.* Although they do orbit the Galactic center, they move in all directions, their paths filling an entire three-dimensional volume rather than a nearly two-dimensional disk. At any given distance from the Galactic center, bulge or halo stars move at speeds comparable to the disk's rotation speed at that radius but in *all* directions, not just one. Their orbits carry these stars repeatedly through the disk plane and out the other side. Figure 23.13 contrasts the motion of bulge and halo stars with the much more regular orbits of stars in the Galactic disk. Some well-known stars in the vicinity of the Sun—the bright giant Arcturus, for example—are actually halo stars that are "just passing through" the disk on orbits that take them far above and below the Galactic plane.

** (Halo stars do, in fact, have some net rotation about the Galactic center, but the rotational component of their motion is overwhelmed by the larger random component. The motion of bulge stars also has a rotational component, larger than that of the halo but still smaller than the random component of stellar motion in the bulge.)*

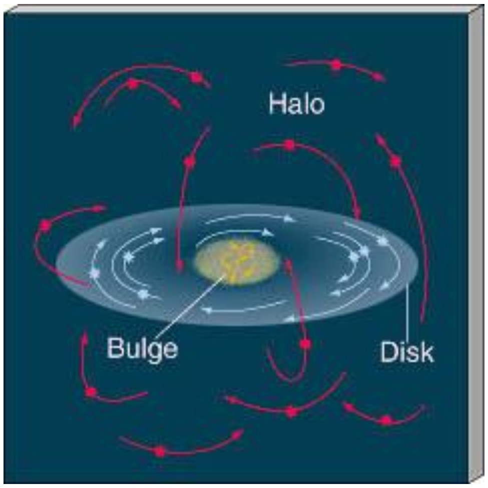

Figure 23.13 *Stars in the Galactic disk move in orderly, circular orbits about the Galactic center. In contrast, halo stars have orbits with largely random orientations and eccentricities. The orbit of a typical halo star takes it high above the Galactic disk, then down through the disk plane, then out the other side and far below the disk. The orbital properties of bulge stars are intermediate between those of disk stars and those of halo stars.*

23.4 The Formation of the Milky Way Galaxy

3 Table 23.1 compares some key properties of the three basic components of the Galaxy. Is there some evolutionary scenario that can naturally account for the Galactic structure we see today? The answer is that there is, and it takes us all the way back to the birth of our Galaxy, 10—15 billion years ago. Not all the details are agreed upon by all astronomers, but the overall picture is now fairly widely accepted. For simplicity we confine our discussion here to the Galactic disk and halo. In many ways the bulge is intermediate in its properties between these two extremes.

TABLE 23.1 Overall Properties of the Galactic Disk, Halo, and Bulge

GALACTIC DISK	**GALACTIC HALO**	**GALACTIC BULGE**
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")

Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances from the center
Contains gas and dust	Contains no gas and dust	Contains gas and dust, especially in the inner regions
Site of ongoing star formation	No star formation during the last 10 billion years	Ongoing star formation in the inner regions
Gas and stars move in circular orbits in the Galactic plane	Stars have random orbits in three dimensions	Stars have largely random orbits but with some net rotation about the Galactic center
Spiral arms	No obvious substructure	Ring of gas and dust near center; Galactic nucleus
Overall white coloration, with blue spiral arms	Reddish in color	Yellow-white

Figure 23.14 illustrates the current view of our Galaxy's evolution, starting (not unlike the star-formation scenario outlined in Chapter 19) from a contracting cloud of pregalactic gas. ∞(Sec. 19.1) When the first Galactic stars and globular clusters formed, the gas in our Galaxy had not yet accumulated into a thin disk. Instead, it was spread out over an irregular, and quite extended, region of space, spanning many tens of kiloparsecs in all directions. When the first stars formed, they were distributed throughout this volume. Their distribution today (the Galactic halo) reflects that fact—it is an imprint of their birth. Many astronomers believe that the very first stars formed even earlier, in smaller systems that later merged to create our Galaxy (Figure 23.14a); the present-day halo would look the same in either case.

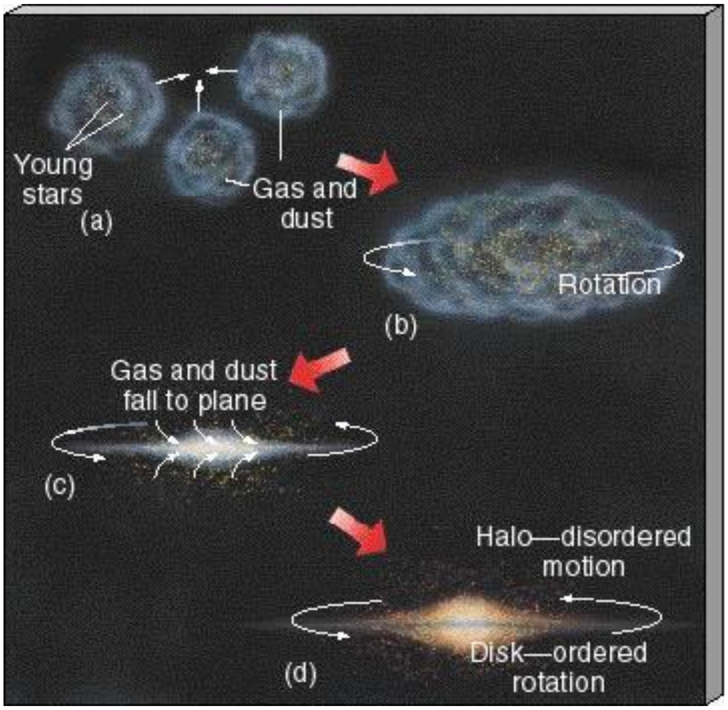

Figure 23.14 *(a) The Milky Way Galaxy possibly formed via the merger of several smaller systems. (b) Astronomers reason that, early on, our Galaxy was irregularly shaped, with gas distributed throughout its volume. When stars formed during this stage, there was no preferred direction in which they moved and no preferred location in which they were found. (c) In time, rotation caused the gas and dust to fall to the Galactic plane and form a spinning disk. The stars that had already formed were left behind, forming the halo. (d) New stars forming in the disk inherit its overall rotation and so orbit the Galactic center on ordered, circular orbits.*

During the past 10—15 billion years, rotation has flattened the gas in our Galaxy into a relatively thin disk. Physically, this process is similar to the flattening of the solar nebula during the formation of the solar system, as described in Chapter 15, except on a vastly larger scale. ∞(Sec. 15.2) Star formation in the halo ceased billions of years ago when the raw materials fell to the Galactic plane. Ongoing star formation in the disk gives it its bluish tint, but the halo's short-lived blue stars have long since burned out, leaving only the long-lived red stars that give it its characteristic pinkish glow. The Galactic halo is ancient, whereas the disk is full of youthful activity. The thick disk, with its intermediate-age stars, may represent an intermediate stage of star formation that occurred while the gas was still flattening into the plane.

The chaotic orbits of the halo stars are also explained by this theory. When the halo developed, the irregularly shaped Galaxy was rotating only very slowly, so there was no strongly preferred direction in which matter tended to move. As a result, halo stars were free to travel along nearly any path once they formed (or when their parent systems merged). As the Galactic disk formed, however, conservation of angular momentum caused it to spin more rapidly. Stars forming from the gas and dust of the disk inherit its rotational motion and so move on well-defined, circular orbits. Again, the thick disk's properties suggest that it formed while gas was still sinking to the Galaxy's midplane and had not yet reached its final (present-day) rotation rate.

In principle, the structure of our Galaxy bears witness to the conditions that created it. In practice, however, the interpretation of the observations is made difficult by the sheer complexity of the system we inhabit and by the many competing physical processes that have modified its appearance since it formed. As a result, the early stages of the Milky Way are still very poorly understood. We will return to the subject of galaxy formation in Chapter 24.

23.5 Spiral Structure

RADIO MAPS OF THE MILKY WAY

If we want to look beyond our immediate neighborhood and study the full extent of the Galactic disk, we cannot rely on optical observations, as interstellar absorption severely limits our vision. In the 1950s, astronomers developed a very important tool to explore the distribution of gas in our Galaxy—spectroscopic radio astronomy.

The keys to observing Galactic interstellar gas are the 21-cm radio emission line produced by atomic hydrogen and the many radio molecular lines formed in molecular cloud complexes. (Sec. 18.4) Long-wavelength radio waves are largely unaffected by interstellar dust, so they travel more or less unimpeded through the Galactic disk, allowing us to "see" to great distances. Because hydrogen is by far the most abundant element in interstellar space, the 21-cm signals are strong enough that a large portion of the disk can be observed in this way. As noted in Chapter 18, observations of spectral lines from "tracer" molecules, such as carbon monoxide, allow us to study the distribution of the densest interstellar clouds. (Sec. 18.5)

Interstellar gas in the Galactic disk exhibits an organized pattern on a grand scale. According to radio studies, the center of the gas distribution coincides roughly with the center of the globular-cluster system, about 8 kpc from the Sun. (In fact, this figure is derived most accurately from radio observations of the distribution of Galactic gas, the center of which is normally taken to define the center of our Galaxy.) Near the center the gas in the disk fattens markedly in the Galactic bulge. Radio-emitting gas has been observed out to at least 50 kpc from the Galactic center. Over much of the inner 20 kpc or so of the disk the gas is confined within about 100 pc of the Galactic plane. Beyond that distance the gas distribution spreads out somewhat, to a thickness of several kiloparsecs, and shows definite signs of being "warped," possibly because of the gravitational influence of a pair of nearby galaxies (to be discussed in Chapter 24; see also Figure 23.15).

Radio studies provide perhaps the best direct evidence that we live in a spiral galaxy. Figure 23.15 is an artist's conception (based on observational data) of the appearance of our Galaxy as seen from far above the disk, clearly showing our Galaxy's **spiral arms**, pinwheel-like structures originating close to the Galactic bulge and extending outward throughout much of the Galactic disk. One of these arms, as best we can tell, wraps around a large part of the disk and contains our Sun. Notice, incidentally, the scale markers on Figures 23.9, 23.10 and 23.15: the Galactic globular-cluster distribution (Figure 23.9), the luminous stellar component of the disk (Figure 23.10), and the known spiral structure (Figure 23.15) all have roughly the *same* diameter—about 30 kpc.

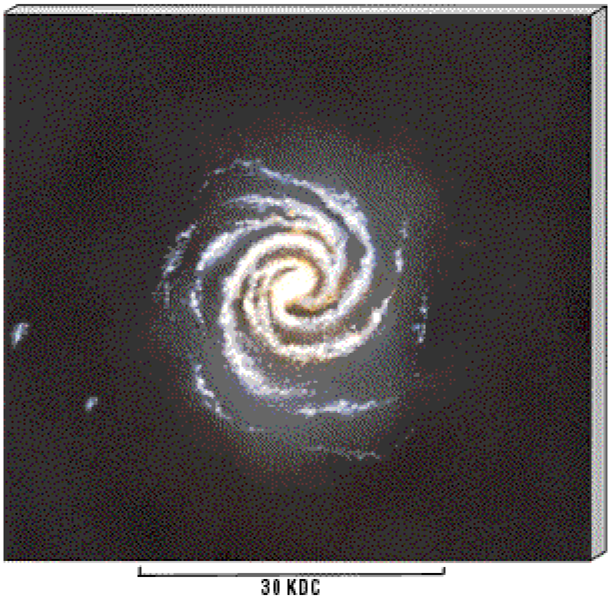

Figure 23.15 *An artist's conception of our Milky Way Galaxy seen face-on. This illustration is based on data accumulated by legions of astronomers during the past few decades, including radio maps of gas density in the Galactic disk. Painted from the perspective of an observer 100 kpc above the Galactic plane, the spiral arms are at their best-determined positions. All the features are drawn to scale (except for the oversized yellow dot near the top, which represents our Sun). The two small blotches to the left are dwarf galaxies, called the Magellanic Clouds. We will study them in Chapter 24.*

PERSISTENCE OF THE SPIRAL ARMS

4 The spiral arms in our Galaxy are made up of much more than just interstellar gas and dust. Studies of the Galactic disk within a kiloparsec or so of the Sun indicate that young stellar and prestellar objects—emission nebulae, O and B stars, and recently formed open clusters—are also distributed in a spiral pattern that closely follows the distribution of interstellar clouds. The obvious conclusion is that the spiral arms are the part of the Galactic disk where star formation takes place. The brightness of the young stellar

objects just listed is the main reason that the spiral arms of other galaxies are easily seen from afar (Figure 23.3a).

A central problem facing astronomers trying to understand spiral structure is how that structure persists over long periods of time. The basic issue is simple: we know that the inner parts of the Galactic disk rotate more rapidly than do the outer regions. Thus stars in the Galactic disk do not move smoothly together, but ceaselessly change their positions relative to one another as they orbit the Galactic center. This differential rotation makes it impossible for any large-scale structure "tied" to the disk material to survive. Figure 23.16 shows how a spiral pattern consisting always of the same group of stars and gas clouds would necessarily "wind up" and disappear within a few hundred million years. Yet spiral arms clearly do exist in our own galaxy, and their prevalence in other disk galaxies suggests that they last for considerably longer than this. Thus, whatever the spiral arms are, they *cannot* simply be dense star-forming regions orbiting along with the rest of the Galactic disk.

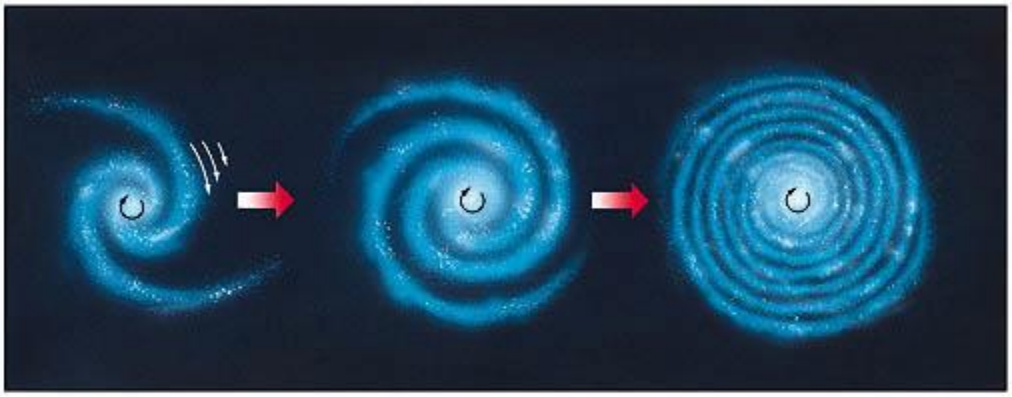

Figure 23.16 *The disk of our Galaxy rotates differentially—stars close to the center take less time to orbit the Galactic center than those at greater distances. If spiral arms were somehow tied to the material of the Galactic disk, this differential rotation would cause the spiral pattern to wind up and disappear in a few hundred million years. Spiral arms would be too short-lived to be consistent with the numbers of spiral galaxies we observe today.*

How then do the Galaxy's spiral arms retain their structure over long periods of time in spite of differential rotation? A leading explanation for the existence of spiral arms holds that they are **spiral density waves**—coiled waves of gas compression that move through the Galactic disk, squeezing clouds of interstellar gas and triggering the process of star formation as they go. ∞(Sec. 19.5) The spiral arms we observe are defined by the denser-than-normal clouds of gas the density waves create and by the new stars formed as a result of the spiral waves' passage.

This explanation of spiral structure avoids the problem of differential rotation because the wave pattern is not tied to any particular piece of the Galactic disk. The spirals we see are merely patterns moving through the disk, not great masses of matter being transported from place to place. The density wave moves through the collection of stars and gas making up the disk just as a sound wave moves through air or an ocean wave passes through water, compressing different parts of the disk at different times. Even though the rotation rate of the disk material varies with distance from the Galactic center, the wave itself remains intact, defining the Galaxy's spiral arms.

In fact, over much of the visible portion of the Galactic disk (within about 15 kpc of the center), the spiral wave pattern is predicted to rotate *more slowly* than the stars and gas. Thus, Galactic material catches up with the wave, is temporarily slowed down and compressed as it passes through, then continues on its way. (For a more down-to-earth example of an analogous process, see *Interlude 23-2*.)

As shown in Figure 23.17, the slowly moving spiral density wave is outrun by the faster-moving disk material. As gas enters the arm from behind, the gas is compressed and forms stars. Dust lanes mark the regions of highest-density gas. The most prominent stars—the bright O and B blue giants—live for only a short time, so young stellar associations, emission nebulae, and open clusters with long main sequences are found only within the arms, near their birth sites, just ahead of the dust lanes. The brightness of these young systems emphasizes the spiral structure. Farther downstream, ahead of the spiral arms, we see mostly older stars and star clusters. These have had enough time since their formation to outdistance the wave and pull away from it. Over millions of years their random individual motions, superimposed on the overall rotation around the Galactic center, distort and eventually destroy their original spiral configuration, and they become part of the general disk population.

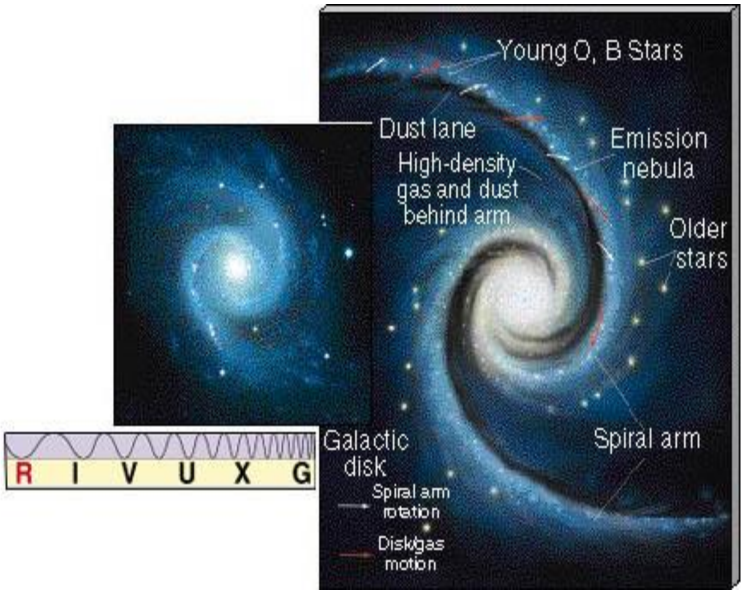

Figure 23.17 *Density-wave theory holds that the spiral arms seen in our own and many other galaxies are waves of gas compression and star formation moving through the material of the galactic disk. In the painting above, gas motion is indicated by red arrows, and arm motion is indicated by white arrows. Gas enters an arm from behind, is compressed, and forms stars. The spiral pattern is delineated by dust lanes, regions of high gas density, and newly formed O and B stars. The inset shows the spiral galaxy NGC 1566, which displays many of the features described in the text. Note, incidentally, that although both spirals here have two arms each, astronomers are not completely certain how many arms make up the spiral structure in our own Galaxy (see Figure 23.15). The theory makes no strong predictions on this point.*

An alternative possibility is that the formation of stars drives the waves, instead of the other way around. Imagine a row of newly formed massive stars somewhere in the disk. As these stars form, the emission nebulae that appear around them send shock waves through the surrounding gas, possibly triggering new star formation. Similarly, when the stars explode in supernovae, more shocks are formed. (Sec. 21.2) As illustrated in Figure 23.18(a), the formation of one group of stars thus provides the mechanism for the creation of more stars. Computer simulations suggest that it is possible for the "wave" of star formation thus created to take on the form of a partial spiral and for this pattern to persist for some time. However, this process, sometimes known as *self-propagating star formation*, can produce only pieces of spirals, as are seen in some galaxies (Figure 23.18b). It apparently cannot produce the galaxywide spiral arms seen in other galaxies and present in our own. It may well be that there is more than one process at work in the spectacular spirals we see.

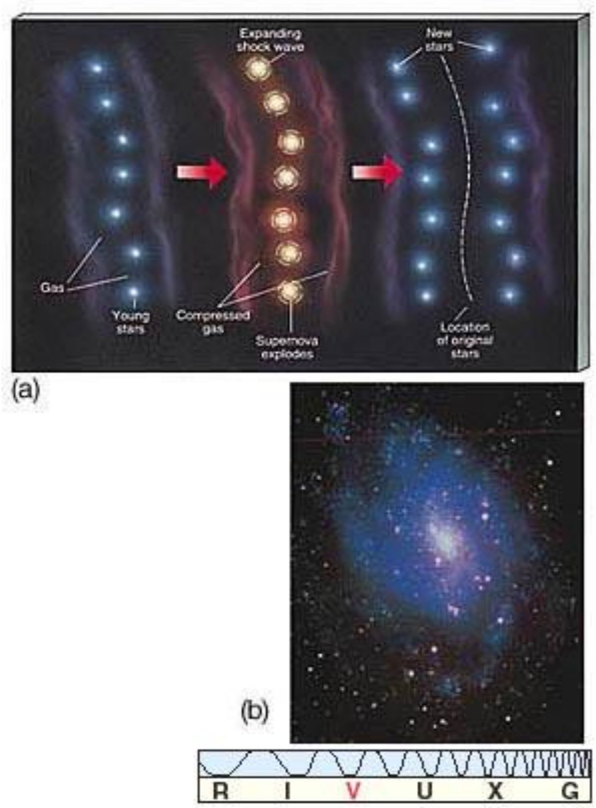

Figure 23.18 *(a) Self-propagating star formation. In this theory of the formation of spiral arms, the shock waves produced by the formation and later evolution of a group of stars provide the trigger for new rounds of star formation. We have used supernova explosions to illustrate the point here, but the formation of emission nebulae and planetary nebulae are also important. (b) This process may well be responsible for the partial spiral arms seen in some galaxies, such as NGC 300, shown here in true color. The distinct blue appearance derives from the vast numbers of young stars that pepper its ill-defined spiral arms.*

An important question (but one that unfortunately is not answered by either of the two theories just described) is: Where do these spirals come from? What was responsible for generating the density wave in the first place or for creating the line of newborn stars whose evolution drives the advancing spiral arm? Scientists speculate that (2) instabilities in the gas near the Galactic bulge, (1) the gravitational effects of our satellite galaxies (the Magellanic Clouds, to be discussed in Chapter 24), or (3) the possible barlike asymmetry within the bulge itself may have had a big enough influence on the disk to get the process going.

The first possibility is supported by growing evidence that many other spiral galaxies seem to have experienced gravitational interactions with neighboring systems in the relatively recent past (see Chapter 24). However, many astronomers still regard the other two possibilities as equally likely. For example, they point to *isolated* spirals, whose structure clearly cannot be the result of an external interaction. The fact is that we still don't know for sure how galaxies—including our own—acquire such beautiful spiral arms.

23.6 The Mass of the Milky Way Galaxy

5 We can measure our Galaxy's mass by studying the motions of gas clouds and stars in the Galactic disk. Recall from Chapter 2 that Kepler's third law (as modified by Newton) connects the orbital period, orbit size, and masses of any two objects in orbit around each other: ∞ (Sec. 2.7)

$$\text{total mass (solar masses)} = \frac{\text{orbit size (A.U.)}^3}{\text{orbit period (years)}^2}.$$

As we saw earlier, the distance from the Sun to the Galactic center is about 8 kpc, and the Sun's orbital period is 225 million years. Substituting these numbers into the preceding equation, we obtain a mass of almost 10^{11} solar masses—100 *billion* times the mass of our Sun. The Milky Way Galaxy is truly enormous, in mass as well as in size.

But what mass have we just measured? When we performed the analogous calculation in the case of a planet orbiting the Sun (Section 1.7), there was no ambiguity: neglecting the planet's mass, the result of our calculation was the mass of the Sun. However, the Galaxy's matter is not concentrated at the Galactic center (as the Sun's mass is concentrated at the center of the solar system); instead, Galactic matter is distributed over a large volume of space. Some of it lies inside the Sun's orbit (that is, within 8 kpc of the Galactic center), and some lies outside, at large distances from both the Sun and the center of the Galaxy. What portion of the Galaxy's mass controls the Sun's orbit? Isaac Newton answered this question three centuries ago: the Sun's orbital period is determined by the portion of the Galaxy that lies *within the orbit of the Sun*. This is the mass computed from the foregoing equation.

DARK MATTER

To determine the mass of the Galaxy on larger scales—that is, to find how much matter is contained within spheres of progressively larger radii—we must measure the orbital motion of stars and gas farther from the Galactic center than is the Sun. Astronomers have found that the most effective way to do this is to make radio observations of gas in the Galactic disk, because radio waves are relatively unaffected by interstellar absorption and allow us to probe to great distances, far beyond the Sun's orbit. On the basis of these studies, radio astronomers have determined our Galaxy's rotation rate at various distances from the Galactic center. The resultant plot of rotation speed versus distance from the center (Figure 23.19) is called the Galactic **rotation curve.**

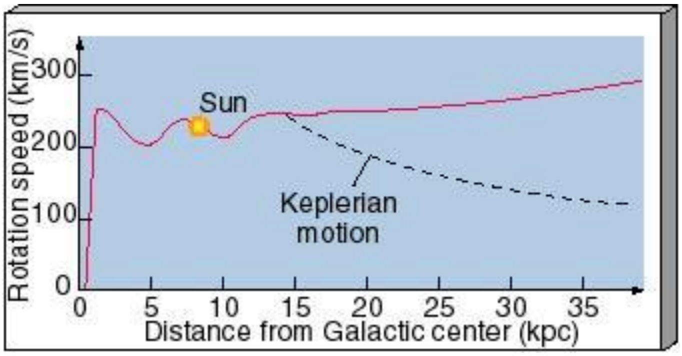

Figure 23.19 *The rotation curve for the Milky Way Galaxy plots rotation speed versus distance from the Galactic center. We can use this curve to compute the mass of the Galaxy that lies within any given radius. The dashed curve is the rotation curve expected if the Galaxy "ended" abruptly at a radius of 15 kpc, the limit of most of the known spiral structure and the globular cluster distribution. The fact that the red curve does not follow this dashed line, but instead stays well above it, indicates that there must be additional matter beyond that radius.*

Knowing the Galactic rotation curve, we can now repeat our earlier calculation to compute the total mass that lies within any given distance from the Galactic center. We find, for example, that the mass within about 15 kpc from the center—the volume defined by the globular clusters and the known spiral structure—is roughly 2×10^{11} solar masses, about twice the mass contained within the Sun's orbit. Does the distribution of matter in the Galaxy "cut off" at this point, where the luminosity drops off sharply? Surprisingly, it does not.

If most of the matter in the Galaxy were contained within the edge of the visible structure, Newton's laws of motion predict that the orbital speed of stars and gas beyond 15 kpc would decrease with increasing distance from the Galactic center, just as the orbital speeds of the planets diminish as we move outward from the Sun. The dashed line in Figure 23.19 indicates what the rotation curve would look like in that case. However, the true rotation curve is quite different. Far from falling off at larger distances, it *rises* slightly out to the limits of our measurement capabilities. This implies that the amount of mass contained within successively larger radii continues to grow beyond the orbit of the Sun, apparently out to a distance of at least 40 or 50 kpc. According to the preceding equation, the amount of mass within 40 kpc is approximately 6×10^{11} solar masses. Since 2×10^{11} solar masses lies within 15 kpc of the Galactic center, we have to conclude that at least twice as much mass lies *outside* the luminous part of our galaxy—the part made up of stars, star clusters, and spiral arms—as lies inside!

Based on these observations of the Galactic rotation curve, astronomers now believe that the luminous portion of the Milky Way Galaxy—the region outlined by the globular clusters and by the spiral arms—is merely the "tip of the Galactic iceberg." Our Galaxy is in reality very much larger. The luminous region is surrounded by an extensive, invisible **dark halo**, which dwarfs the inner halo of stars and globular clusters and extends well beyond the 15-kpc radius once thought to represent the limit of our Galaxy. But what is the composition of this dark halo? We do not detect enough stars or interstellar matter to account for the mass that our computations tell us must be there. We are inescapably drawn to the conclusion that most of the mass in our Galaxy exists in the form of invisible **dark matter**, which we presently simply do not understand.

The term *dark* here does not refer just to matter undetectable in visible light. The material has (so far) escaped detection at *all* wavelengths, from radio to gamma rays. Only by its gravitational pull do we know of its existence. Dark matter is not hydrogen gas (atomic or molecular), nor is it made up of ordinary stars. Given the amount of matter that must be accounted for, we would have been able to detect it with present-day equipment if it were in either of those forms. Its nature and its consequences for the evolution of galaxies and the universe are among the most important questions in astronomy today. Many candidates have been suggested for this dark matter, although none is proven. Black holes may supply some of the unseen mass, although their very existence is still debated, and very few candidates exist. (Sec. 22.7) However, given that black holes are the evolutionary products of (relatively rare) massive stars, it is unlikely that there could be enough of them to hide large amounts of Galactic matter. Currently among the strongest "stellar" contenders are brown dwarfs—low-mass prestellar objects that never reached the point of core nuclear burning—white dwarfs, and faint, low-mass red dwarfs. (Secs. 19.3, 20.3) These objects could in principle exist in great numbers throughout the Galaxy yet would be exceedingly hard to see.

Recent *Hubble Space Telescope* observations of globular clusters seem to argue against at least the last of these possibilities. Figure 23.20 shows a *Hubble* image of a relatively nearby globular cluster—one close enough that very faint red dwarfs could have been detected if any existed. The *Hubble* data suggest that there is a cutoff at about 0.2 solar masses, below which stars form much less frequently than had previously been supposed. As a result, very low-mass stars seem to be unexpectedly rare in our Galaxy.

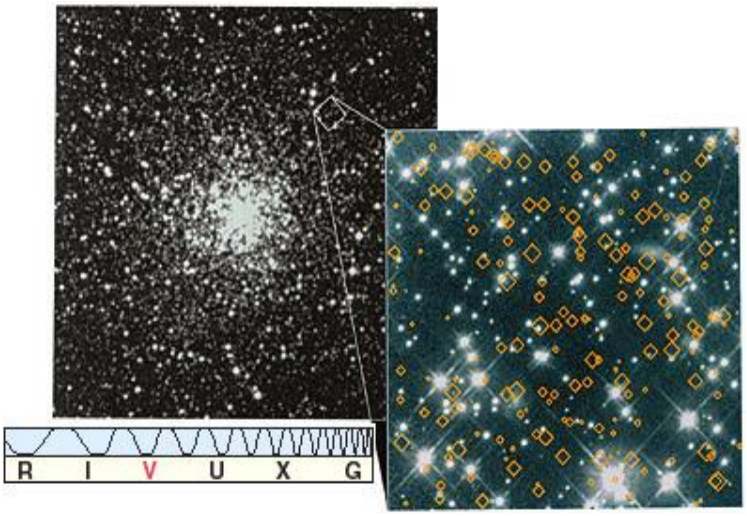

Figure 23.20 *Very sensitive visible observations with the Hubble Space Telescope have apparently ruled out faint red-dwarf stars as candidates for dark matter. The object shown here, the globular cluster NGC 6397, is one of many regions searched in the Milky Way. The inset, 0.4 pc on a side, shows a high-resolution Hubble view. The scores of diamonds have been overlaid at positions where red dwarfs might (statistically) have been expected if they did indeed make up the dark matter, but they were not found.*

A radically different alternative is that the dark matter is made up of exotic *subatomic particles* that pervade the entire universe. Many theoretical astrophysicists believe that these particles could have been produced in abundance during the very earliest moments of our universe. If the particles have survived to the present day, there might be enough of them to account for all the dark matter we believe must be out there. This idea is hard to test, however, because any particles of this nature that might exist would be very hard to detect. Several detection experiments have been attempted, so far without success.

THE SEARCH FOR STELLAR DARK MATTER

Recently, researchers have obtained insight into the distribution of stellar dark matter by using a key element of Albert Einstein's theory of general relativity—the prediction that a beam of light can be deflected by a gravitational field, which has already been verified in the case of starlight that passes close to the Sun ∞ (*More Precisely 22-2*). Although this effect is small, it has the potential for making otherwise invisible stellar objects observable from Earth. Here's how.

Imagine looking at a distant star as a faint foreground object (such as a brown dwarf or a white dwarf) happens to cross your line of sight. As illustrated in Figure 23.21, the intervening object deflects a little more starlight than usual toward you, resulting in a temporary, but quite substantial, *brightening* of the distant star. In some ways, the effect is like the focusing of light by a lens, and the process is known as **gravitational lensing**. The foreground object is referred to as a *gravitational lens*. The amount of brightening and the duration of the effect depend on the mass, distance, and speed of the lensing object. Typically, the apparent brightness of the background star increases by a factor of 2 to 5 for a period of several weeks. Thus, even though the foreground object cannot be seen directly, its effect on the light of the background star makes it detectable. (In Chapter 25 we will encounter other instances of gravitational lensing in the universe, but on very much larger scales.)

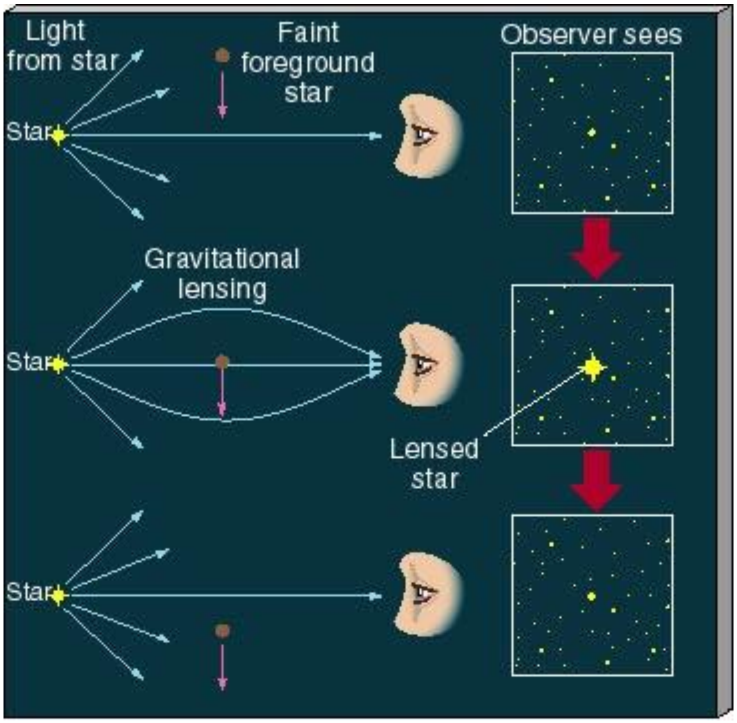

Figure 23.21 *Gravitational lensing by a faint foreground object (such as a brown dwarf) can temporarily cause a background star to brighten significantly, providing a means of detecting otherwise invisible stellar dark matter.*

Of course, the probability that one star will pass almost directly in front of another, as seen from Earth, is extremely small. But by observing millions of stars every few days over a period of years (using automated telescopes and high-speed computers to reduce the burden of coping with so much data), astronomers have been able to see enough of these events to let them estimate the amount of stellar dark matter in the Galactic halo. The technique represents an exciting new means of probing the structure of our Galaxy. The first lensing events were reported in late 1993. Subsequent observations are consistent with lensing by low-mass white dwarfs and suggest that such stars could account for at least half of the dark matter inferred from dynamical studies.

Bear in mind, though, that the identity of the dark matter is not necessarily an all-or-nothing proposition. It is perfectly conceivable that more than one type of dark matter exists. For example, it is quite possible that most of the dark matter in the inner (visible) parts of galaxies is in the form of brown dwarfs and very-low-mass stars, while the dark matter farther out may be primarily in the form of exotic particles. We will return to this perplexing problem in later chapters.

23.7 The Galactic Center

Theory predicts that the Galactic bulge, and especially the region close to the Galactic center, should be densely populated with billions of stars. However, we are unable to see this region of our Galaxy—the interstellar medium in the Galactic disk shrouds what otherwise would be a stunning view. Figure 23.22 shows the (optical) view we do have of the region of the Milky Way toward the Galactic center, in the general direction of the constellation Sagittarius.

Figure 23.22 *A photograph of stellar and interstellar matter in the direction of the Galactic center. Because of heavy obscuration, even the largest optical telescopes can see no farther than 1/10 the distance to the center. The M8 nebula (arrow) can be seen at extreme top center. The field is roughly 20 °, top to bottom, and is a continuation of the bottom part of Figure 18.6. The circle indicates the location of the center of our Galaxy.*

With the help of infrared and radio techniques we can peer more deeply into the central regions of our Galaxy than we can by optical means. Infrared observations (Figure 23.23a) indicate that the heart of our Galaxy harbors roughly 50,000 stars per cubic parsec. That's a stellar density about a million times greater than in our solar neighborhood, high enough that stars must experience frequent close encounters and even collisions. Infrared radiation has also been detected from what appear to be huge clouds rich in dust. In addition, radio observations indicate a ring of molecular gas nearly 400 pc across, containing some 30,000 solar masses of material and rotating at about 100 km/s. The origin of this ring is unclear, although researchers suspect that the gravitational influence of our Galaxy's elongated, rotating bulge may well be involved. The ring surrounds a bright radio source that marks the Galactic center.

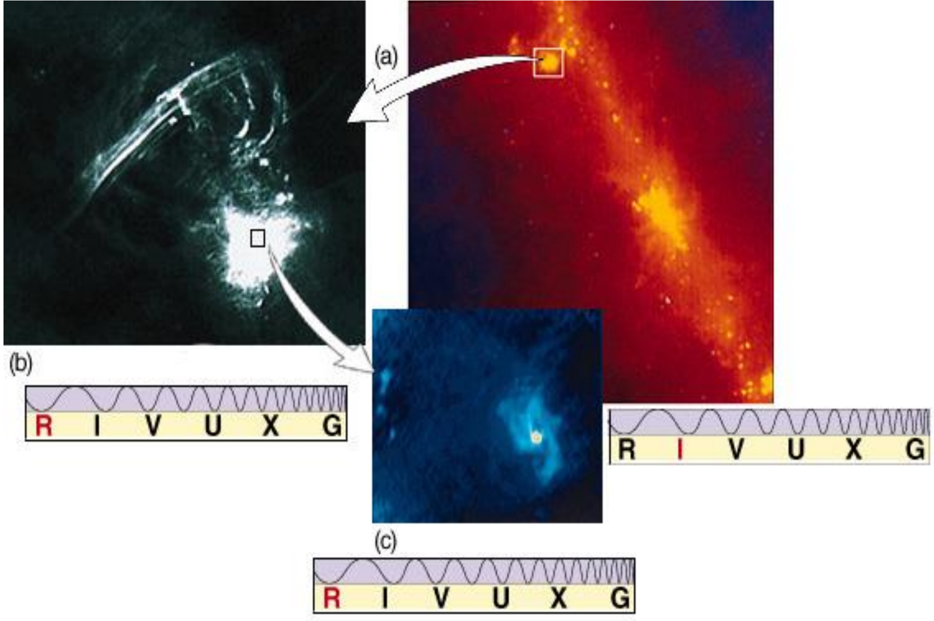

Figure 23.23 *(a) An infrared image of the region around the center of our Galaxy shows many bright stars packed into a relatively small volume. The average density of matter in this region is estimated to be about a million times that in the solar neighborhood. (b) The central portion of our Galaxy, as seen in the radio part of the spectrum. This image shows a region about 200 pc across surrounding the Galactic center (which lies within the bright blob at bottom right). The long-wavelength radio emission cuts through the Galaxy's dust, providing an image of matter in the immediate vicinity of the Galaxy's center. (c) The spiral pattern of radio emission arising*

from Sagittarius A, the very center of the Galaxy. The data suggest a rotating ring of matter only 5 pc across.

High-resolution radio observations show more structure on small scales. Figure 23.23(b) shows the bright radio source Sagittarius A, which lies at the center of the circle in Figure 23.22 and within the boxed region in Figure 23.23(a) and, we think, at the center of our Galaxy. On a scale of about 100 pc, extended filaments can be seen. Their presence suggests to many astronomers that strong magnetic fields operate in the vicinity of the center, creating structures similar in appearance to (but much larger than) those observed on the active Sun. On even smaller scales (Figure 23.23c) the observations indicate a rotating ring or disk of matter only a few parsecs across.

What could cause all this activity? An important clue comes from the Doppler broadening of infrared spectral lines emitted from the central swirling whirlpool of gas. The extent of the broadening indicates that the gas is moving very rapidly. In order to keep this gas in orbit, whatever is at the center must be extremely massive—a million solar masses or more. Given the twin requirements of large mass and small size, a leading contender is a black hole. The hole itself is not the source of the energy, of course. Instead, the vast accretion disk of matter being drawn toward the hole by the enormous gravity emits the energy as it falls in, just as we saw (on a much smaller scale) in Chapter 22 when we discussed X-ray emission from neutron stars and stellar-mass black holes ∞∞(Secs. 22.3, 22.7) The strong magnetic fields are thought to be generated within the accretion disk as matter spirals inward, and may act as "particle accelerators," creating the extremely high-energy particles detected on Earth as *cosmic rays* (see *Interlude 23-3*). Astronomers have reason to suspect that similar events are occurring at the centers of many other galaxies.

Figure 23.24 places these findings into a simplified perspective. Each frame is centered on the Galaxy's core, and each increases in resolution by a factor of 10. Frame (a) renders the Galaxy's overall shape, as painted in Figure 23.15. The scale of this frame measures about 100 kpc from top to bottom. Frame (b) spans a distance of 10 kpc from top to bottom and is nearly filled by the great circular sweep of the innermost spiral arm. Moving in to a 1-kpc span, frame (c) depicts the 400-pc ring of matter mentioned earlier. The dark blobs represent giant molecular clouds, the pink patches emission nebulae associated with star formation within those clouds.

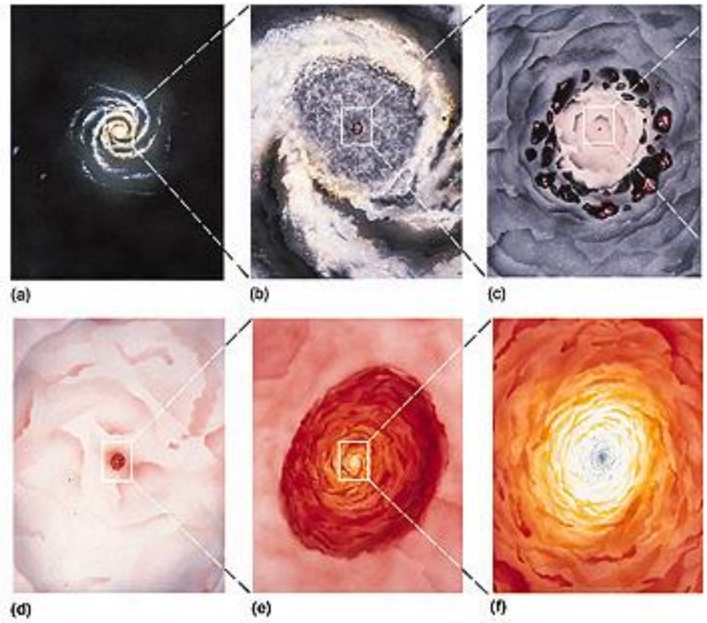

Figure 23.24 *Six artist's conceptions, each centered on the Galactic center and each increasing in resolution by a factor of 10. Frame (a) shows the same scene as Figure 23.15. Frame (f) is a rendition of a vast whirlpool within the innermost parsec of our Galaxy. The data imaged in Figure 23.23 do not*

closely match these artistic renderings because the Figure 23.23 view is parallel to the Galactic disk, whereas these six paintings portray an idealized version perpendicular to that disk.

In frame (d), at 100 pc, a pinkish region of ionized gas surrounds the reddish heart of the Galaxy. The source of energy producing this vast ionized cloud is assumed to be related to the activity in the Galactic center. Frame (e), spanning 10 pc, depicts the tilted, spinning whirlpool of hot (10^4 K) gas that marks the center of our Galaxy. The innermost part of this gigantic whirlpool is painted in frame (f), in which a swiftly spinning, white-hot disk of gas with temperatures in the millions of kelvins nearly engulfs a massive black hole too small in size to be pictured (even as a minute dot) on this scale.

At the very center of our Galaxy is a remarkable object with the odd-sounding name Sgr A* (pronounced "saj-ay-star"). By the standards of the active galaxies to be studied in Chapter 25, this compact galactic nucleus is not particularly energetic. Still, radio observations made during the past two decades, along with more recent X- and gamma-ray observations, suggest that it is nevertheless a pretty violent place. Its total energy output (at all wavelengths) is estimated to be 10^{33} W, which is more than a million times that of the Sun.

VLBI observations using radio telescopes arrayed from Hawaii to Massachusetts imply that Sgr A* cannot be much larger than 10 A.U., and it is probably a good deal smaller than that. This size is consistent with the view that the energy source is a massive black hole, although the case is not airtight. The main alternatives are that Sgr A* could be a multiple supernova of some sort (but we detect no expansion of debris), a rapidly moving neutron star (but Sgr A* seems to be more or less fixed relative to the surrounding galaxy), a large star cluster (but the energy-emitting region seems far too small), or even an ordinary neutron star embedded within a very unusual radio source (but that seems too ad hoc).

Some recent findings support the black hole picture. Infrared spectroscopic observations of two dozen stars within a few arc seconds of Sgr A* indicate that their orbital speeds are greater the closer they are to the center—just as one would expect for matter orbiting near a large black hole. In addition, an adaptive-optics infrared imaging camera has spotted a bright source very close to Sgr A* that seems to vary with a 10-minute period; this could be a hot spot on the accretion disk that circles the purported hole. The accumulated data imply that Sgr A* contains about 1—2 million solar masses. Even with this large mass, if Sgr A* is a genuine black hole, then the size of its event horizon is still only 0.02 A.U. Such a small region, 8 kpc away, is currently unresolvable with any telescope now in existence.

If our knowledge of the Galaxy's center seems sketchy, that's because it *is* sketchy. Astronomers are still deciphering the clues hidden within its invisible radiation. We are only beginning to appreciate the full magnitude of this strange new realm deep in the heart of the Milky Way.

Chapter Review

SUMMARY

A **galaxy** is a huge collection of stellar and interstellar matter isolated in space and bound together by its own gravity. Because we live within it, the **Galactic disk** of our own **Milky Way Galaxy** appears as a broad band of light across the sky, a band called the Milky Way. Near the center, the Galactic disk thickens into the **Galactic bulge**. The disk is surrounded by a roughly spherical **Galactic halo** of old stars and star clusters. Our Galaxy, like many others visible in the sky, is a **spiral galaxy.**

The halo can be studied using **variable stars**, whose luminosity changes with time. **Pulsating variable stars** vary in brightness in a repetitive and predictable way. Two types of pulsating variable stars of great importance to astronomers are **RR Lyrae** variables and **Cepheid** variables, whose characteristic light curves make them easily recognizable. All RR Lyrae stars have roughly the same luminosity. Astronomers can determine the luminosity of Cepheids by measuring the pulsation period and using the **period—luminosity relationship**, a simple correlation between period and absolute brightness. The brightest Cepheids can be seen at distances of millions of parsecs, extending the cosmic distance ladder well beyond our own Galaxy. RR Lyrae stars are fainter but much more numerous, making them very useful within the Milky Way.

In the early twentieth century, Harlow Shapley used RR Lyrae stars to determine the distances to many of the Galaxy's globular clusters. He found that the clusters have a roughly spherical distribution in space, but the center of the sphere lies far from the Sun. The globular clusters are now known to map out the true extent of the luminous portion of the Milky Way Galaxy. The center of their distribution is close to the **Galactic center**, which lies about 8 kpc from the Sun.

Disk and halo stars differ in their spatial distributions, ages, colors, and orbital motion. The luminous portion of our Galaxy has a diameter of about 30 kpc. The halo lacks gas and dust, so no stars are forming there. All halo stars are old. The gas-rich disk is the site of current star formation and contains many young stars. Stars and gas within the Galactic disk move on roughly circular orbits around the Galactic center. Stars in the halo and bulge move on largely random three-dimensional orbits that pass repeatedly through the disk plane but have no preferred orientation. Halo stars appeared early on, before the Galactic disk took shape, when there was still no preferred orientation for their orbits. As the gas and dust formed a rotating disk, stars that formed in the disk inherited its overall spin and so moved on circular orbits in the Galactic plane, as they do today.

In the vicinity of the Sun the Galactic disk is about 300 pc thick. Young stars, gas, and dust are more narrowly confined; older stars have a broader distribution. Intermediate between the young disk and the old halo, in both age and spatial distribution, are the stars of the **thick disk**, which is about 2-3 kpc thick.

Attempts to map out the Galactic disk by optical observations are defeated by interstellar absorption. Astronomers use radio observations to explore the Galactic disk because radio waves are largely unaffected by interstellar dust. Regions where most of the hydrogen is in atomic form may be studied using 21-cm radiation. Regions where the gas is mostly molecular are studied through radio molecular emission lines. Gas has been detected in the disk at up to 50 kpc from the Galactic center. Regions where the gas is mostly molecular are usually studied by observing radio emission lines from "tracer" molecules, such as carbon monoxide. The gas distribution fattens near the center into the Galactic bulge. Radio-emitting gas has been detected in the disk at up to 50 kpc from the Galactic center.

Radio observations clearly reveal the extent of our Galaxy's **spiral arms**. The spiral arms in spiral galaxies are regions of the densest interstellar gas and are the places where star formation is taking place. The spirals cannot be "tied" to the disk material, as the disk's differential rotation would have wound them up long ago. Instead, they may be **spiral density waves** that move through the disk, triggering star formation as they pass by. Alternatively, the spirals may arise from self-propagating star formation, when shock waves produced by the formation and evolution of one generation of stars triggers the formation of the next.

The Galactic **rotation curve** plots the orbital speed of matter in the disk versus distance from the Galactic center. By applying Newton's laws of motion, astronomers can determine the mass of the Galaxy. They find that the Galactic mass continues to increase beyond the radius defined by the globular clusters and the spiral structure we observe. The rotation curves of our own and other galaxies show that many, if not all, galaxies have an invisible **dark halo** containing far more mass than the visible portion of the galaxies. The **dark matter** making up these dark halos is of unknown composition. Leading candidates include low-mass stars and exotic subatomic particles. Recent attempts to detect stellar dark matter have used the fact that a faint foreground object can occasionally pass in front of a more distant star, deflecting the star's light and causing its apparent brightness to increase temporarily. This deflection is called **gravitational lensing**.

Astronomers working at infrared and radio wavelengths have uncovered evidence of energetic activity within a few parsecs of the Galactic center. The leading explanation is that a black hole 1 million times more massive than the Sun resides at the heart of our Galaxy.

SELF-TEST: TRUE OR FALSE?

1. Cepheids can be used to determine the distances to the nearest galaxies.

2. RR Lyrae stars are a type of cataclysmic variable.

3. The Galactic halo contains about as much gas and dust as the Galactic disk.
4. The Galactic disk contains only old stars.
5. Population I objects are found only in the Galactic halo.
6. Up until the 1930s, the main error made in determining the size of the Galaxy was due to an incorrectly calibrated method of determining stellar distances.
7. Astronomers use 21-cm radiation to study Galactic molecular clouds.
8. Radio techniques are capable of mapping the entire Galaxy.
9. In the neighborhood of the Sun, the Galaxy's spiral density wave rotates more slowly than the overall Galactic rotation.
10. The mass of the Galaxy is determined by counting stars.
11. Dark matter is now known to be due to large numbers of black holes.
12. A million—solar mass black hole could account for the unusual properties of the Galactic center.
13. Cosmic rays are very energetic photons.
14. Most of the mass of our Galaxy exists in the form of dark matter.
15. The Galactic center has been extensively studied at visible and ultraviolet wavelengths.

SELF-TEST: FILL IN THE BLANK

1. One difficulty in studying our own galaxy in its entirety is that we live _____.
2. Herschel's attempt to map the Milky Way by counting stars led to an inaccurate estimate of the Galaxy's size because he was unaware of _____.
3. The highly flattened, circular part of the Galaxy is called the Galactic _____.
4. The roughly spherical region of faint old stars and globular clusters in which the rest of the Galaxy is embedded is the Galactic _____.
5. Cepheids and RR Lyrae stars are observed to vary in _____ with periods of days to months.
6. Cepheid pulsational periods range from _____ to _____.
7. Cepheids and RR Lyrae variables lie in a region of the H—R diagram called the _____.
8. According to the period—luminosity relation, the longer the pulsation period of a Cepheid, the _____ its luminosity.
9. Harlow Shapley determined the distances to the globular clusters using observations of _____.
10. The Sun lies roughly _____ pc from the Galactic center.
11. The orbital speed of the Sun around the Galactic center is _____.
12. The orbits of halo objects are _____ in direction.
13. The original cloud of gas from which the Galaxy formed probably had a size and shape similar to the present Galactic _____.
14. Rotational velocities in the outer part of the Galaxy are _____ than would be expected on the basis of observed stars and gas, indicating the presence of _____.
15. Observations of the _____ of infrared spectral lines indicate that gas near the Galactic center is orbiting at extremely high speeds.

REVIEW AND DISCUSSION

1. What are spiral nebulae? How did they get that name?
2. How are Cepheid variables used in determining distances?
3. Roughly how far out into space can we use Cepheids to measure distance?
4. What important discoveries were made early in this century using RR Lyrae variables?
5. Why are the central regions of our Galaxy best studied using radio telescopes?
6. Of what use is radio astronomy in the study of Galactic structure?
7. Contrast the motions of disk and halo stars.
8. Explain why Galactic spiral arms are believed to be regions of recent and ongoing star formation.
9. Describe what happens to interstellar gas as it passes through a spiral density wave.
10. What is self-propagating star formation?
11. What do the red stars in the Galactic halo tell us about the history of the Milky Way?

12. What does the rotation curve of our Galaxy tell us about its total mass?
13. What evidence is there for that dark matter in the Galaxy?
14. What are some possible explanations for dark matter?
15. Why do astronomers believe that a supermassive black hole lies at the center of the Milky Way?