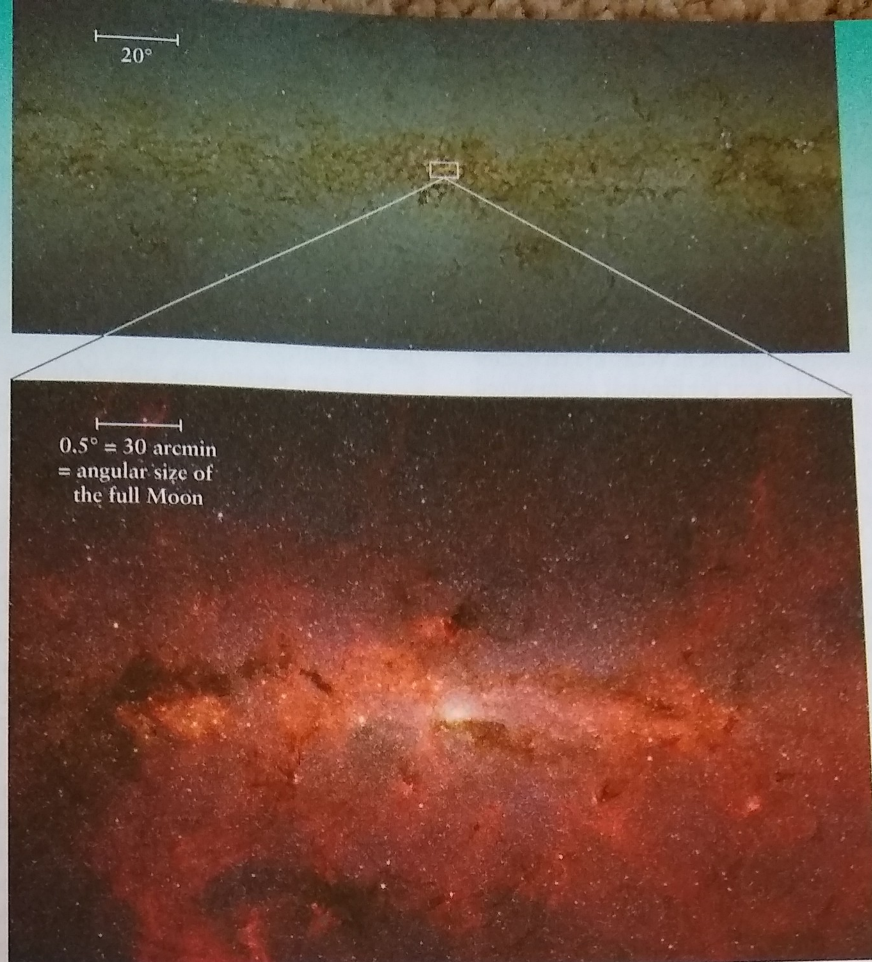


Two views of the Milky Way: a wide-angle infrared image (upper) and a close-up infrared image (lower). *(upper: Ohainaut/ESO/Handout/dpa/Corbis; lower: NASA/JPL-Caltech/S. Stolovy [SSC/Caltech])*

CHAPTER 22

Our Galaxy

LEARNING GOALS

By reading the sections of this chapter, you will learn

22-1 How astronomers discovered the solar system's location within the Milky Way Galaxy

22-2 The shape and size of our Galaxy

22-3 How the Milky Way's spiral structure was discovered

22-4 The evidence for the existence of dark matter in our Galaxy

22-5 What causes the Milky Way's spiral arms to form and persist

22-6 How astronomers discovered a supermassive black hole at the galactic center

On a clear, moonless night, away from the glare of city lights, you can often see a hazy, luminous band stretching across the sky. This band, called the Milky Way, extends all the way around the celestial sphere. The upper of the two accompanying photographs is centered on the brightest part of the Milky Way, in the constellation Sagittarius.

Galileo, the first person to view the Milky Way with a telescope, discovered that it is composed of countless dim stars. Today, we realize that the Milky Way is actually a disk tens of thousands of parsecs across containing hundreds of billions of stars. (It is hard to picture hundreds of billions of stars, but it is about the number of grains in a few trashcans full of beach sand.) Between the stars, there are also large quantities of gas and dust. One of these stars is our Sun, and this vast assemblage of matter—our home galaxy—is collectively called the Milky Way Galaxy.

Just as Galileo's telescope revealed aspects of the Milky Way that the naked eye could not, modern astronomers use telescopes at nonvisible wavelengths to peer through our Galaxy's obscuring dust and observe what visible-light telescopes never could. For example, the lower of the two accompanying photographs is an infrared image that shows hundreds of thousands of stars near the center of the Galaxy. As we will see, radio, infrared, and X-ray observations reveal that at the very center of the Galaxy lies a black hole with a mass of 4.1 million Suns.

Modern astronomers have also discovered that most of the Milky Way's mass is not in its stars, gas, or dust, but in a halo of *dark matter* that emits no measurable radiation. What the character of this dark matter could be remains one of the greatest unanswered questions in astronomy and physics.

The Milky Way is just one of myriad *galaxies,* or systems of stars and interstellar matter, that are spread across the observable universe. By studying our home galaxy, the Milky Way Galaxy, we begin to explore the universe on a grand scale. Instead of focusing on individual stars, we look at the overall arrangement and history of a huge stellar community of which the Sun is a member. In this way, we gain insights into galaxies in general and prepare ourselves to ask fundamental questions about the cosmos.

22-1 The Sun is located in the disk of our Galaxy, about 8000 parsecs from the galactic center

TUTORIAL 22-1

Eighteenth-century astronomers were the first to suspect that because the Milky Way completely encircles us, all the stars in the sky are part of an enormous disk of stars—the Milky Way Galaxy. As we learned in Section 1-4, a **galaxy** is an immense collection of stars—as well as gas and dust referred to as **interstellar matter.**

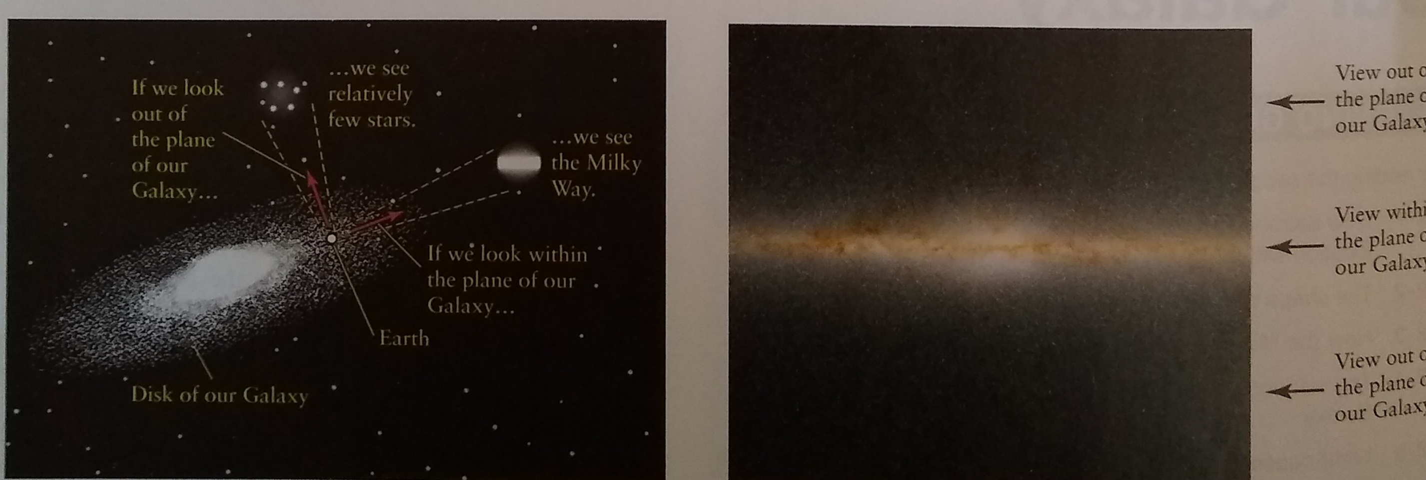
Our Galaxy is both large and mostly empty. To put our Galaxy into perspective, consider this scale model suggested by astronomer Mark Whittle: Suppose that our Galaxy was shrunk down to the size of the continental United States. Then, the average distance between the shrunken stars would be about the size of a football field. But what about the stars themselves? The average size of the shrunken stars would be about the size of human cells! Clearly, the stars of the Milky Way are widely separated, and there are a lot of them.

We are within our own Milky Way Galaxy, which makes it hard to view. Our solar system is located inside the pancakelike disk of our Galaxy, which is why the Milky Way appears as a band around the sky (Figure 22-1).

Locating the Sun Within the Galaxy: Early Attempts

But where within this disk is our own Sun? Until the twentieth century, the prevailing opinion was that the Sun and planets lie at the Galaxy's center. One of the first to come to this conclusion was the eighteenth-century English astronomer William Herschel, who discovered the planet Uranus and was a pioneering cataloger of binary star systems (see Section 17-9). Herschel's approach to determining the Sun's position within the Galaxy was to count the number of stars in each of 683 regions of the sky. He reasoned that he should see the greatest number of stars toward the Galaxy's center and a lesser number toward the Galaxy's edge.

Herschel found approximately the same density of stars all along the Milky Way. Therefore, he concluded that we are at the center of our Galaxy (Figure 22-2). In the early 1900s, the Dutch astronomer Jacobus Kapteyn came to essentially the same conclusion by analyzing the brightness and proper motions of a large number of stars. According to Kapteyn, the Milky Way is about 17 kpc (17 kiloparsecs = 17,000 parsecs or 55,000 light-years) in diameter, with the Sun near its center.



(a)

(b) R I V U X G

FIGURE 22-1

Our View of the Milky Way **(a)** The Milky Way Galaxy is a disk-shaped collection of stars. When we look out at the night sky in the plane of the disk, the stars appear as a band of light that stretches all the way around the sky. When we look perpendicular to the plane of the Galaxy, we see only those relatively few stars that lie between us and the "top" or "bottom" of the disk.

(b) This wide-angle photograph shows a 180° view of the Milky Way centered on the constellation Sagittarius (compare with the photograph that opens this chapter). The dark streaks across the Milky Way are due to interstellar dust in the plane of our Galaxy. (b: Stocktrek Images/Getty Images)

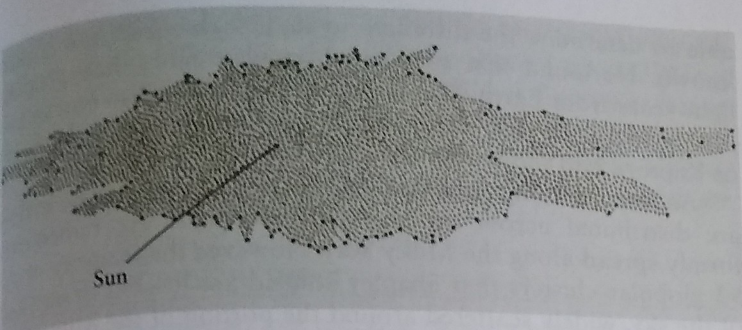


FIGURE 22-2
Herschel's Map of Our Galaxy In a paper published in 1785, the English astronomer William Herschel presented this map of the Milky Way Galaxy. He determined the Galaxy's shape by counting the numbers of stars in various parts of the sky. Herschel's conclusions were flawed because interstellar dust blocked his view of distant stars, leading him to the erroneous idea that the Sun is at the center of the Galaxy. (Dr. Jeremy Burgess/Science Source)

The Problem: Interstellar Extinction

Both Herschel and Kapteyn were wrong about the Sun being at the center of our Galaxy. The reason for their mistake was discerned in 1930 by Robert J. Trumpler of Lick Observatory. While studying star clusters, Trumpler discovered that the more remote clusters appear unusually dim—more so than would be expected from their distances alone. As a result, Trumpler concluded that interstellar space must not be a perfect vacuum: It must contain dust that absorbs or scatters light from distant stars.

Like the stars themselves, interstellar dust is concentrated in the plane of the Galaxy (see Section 18-2). As a result, it obscures our view within the plane and makes distant objects appear dim, an effect called **interstellar extinction**. Great patches of interstellar dust are clearly visible in wide-angle photographs such as the ones that open this chapter. Thanks to interstellar extinction, Herschel and Kapteyn were actually seeing only the nearest stars in the Galaxy. Hence, they had no idea of either the enormous size of the Galaxy or of the vast number of stars concentrated around the galactic center.

ANALOGY Herschel and Kapteyn faced much the same dilemma as a lost motorist on a foggy night. Unable to see more than a city block in any direction, the motorist would have a hard time deciding what part of town he was in. If the fog layer were relatively shallow, however, our motorist would be able to see the lights from tall buildings that extend above the fog, and in that way he could determine his location (Figure 22-3a).

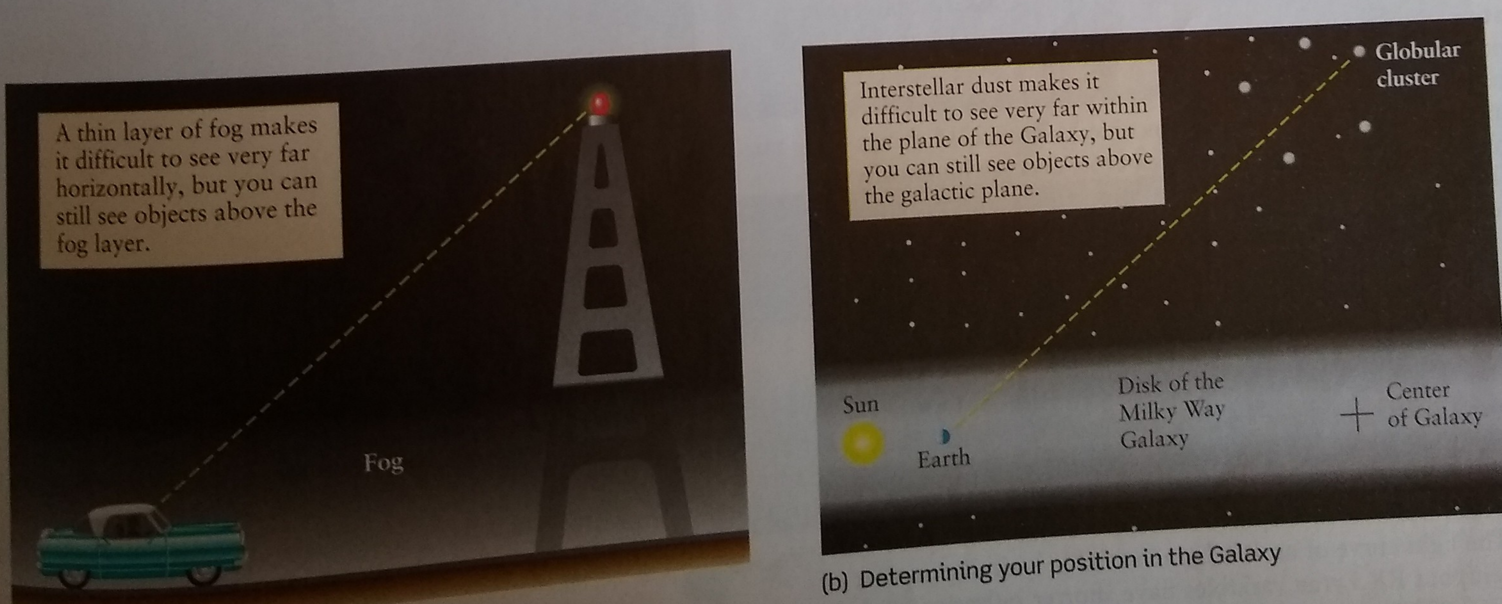
The same principle applies to our Galaxy. While interstellar dust in the plane of our Galaxy hides the sky covered by the Milky Way, we have an almost unobscured view out of the plane (that is, to either side of the Milky Way). To find our location in the Galaxy, we need to locate bright objects that are part of the Galaxy but lie outside its plane in unobscured regions of the sky.

The Breakthrough: Globular Clusters and Variable Stars

Fortunately, bright objects of the sort we need do in fact exist. They are the **globular clusters**, a class of star clusters associated with the Galaxy but which lie outside its plane (Figure 22-3b). As we saw in Section 19-4, a typical globular cluster is a spherical distribution of roughly 10^6 stars packed in a volume only a few hundred light-years across (see Figure 19-12).

However, to use globular clusters to determine our location in the Galaxy, we must first determine the distances from Earth to these clusters. (Think

Observations of pulsating variable stars revealed the immense size of the Milky Way



(a) Determining your position in the fog

(b) Determining your position in the Galaxy

FIGURE 22-3
Finding the Center of the Galaxy (a) A motorist lost on a foggy night can determine his location by looking for tall buildings that extend above the fog. (b) In the same way, astronomers determine our location in the Galaxy by observing globular clusters that are part of the Galaxy but lie outside th obscuring material in the galactic disk. The globular clusters form a spher halo centered on the center of the Galaxy.

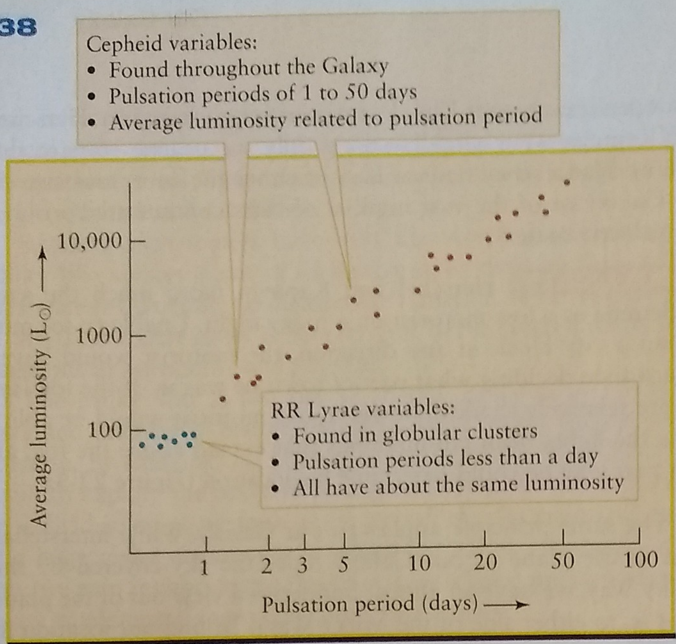


FIGURE 22-4
Period and Luminosity for Cepheid and RR Lyrae Variables This graph shows the relationship between period and average luminosity for Cepheid variables and RR Lyrae variables. Cepheids come in a broad range of luminosities: The more luminous the Cepheid, the longer its pulsation period. By contrast, RR Lyrae variables are horizontal branch stars that all have roughly the same average luminosity of about 100 $L_{\odot}$.

again of our lost motorist—glimpsing the lights of a skyscraper through the fog may be useful to the motorist, but only if he can tell how far away the skyscraper is.) Pulsating variable stars in globular clusters provide the distances, giving astronomers the key to the dimensions of our Galaxy.

In 1912, the American astronomer Henrietta Leavitt reported her important discovery of the period-luminosity relation for Cepheid variables. As we saw in Section 19-6, Cepheid variables are pulsating stars that vary periodically in brightness (see Figure 19-18). Leavitt studied numerous Cepheids in the Small Magellanic Cloud (a small galaxy near the Milky Way) and found their periods to be directly related to their average luminosities. Figure 22-4 shows that the longer a Cepheid's period, the greater its average luminosity.

The period-luminosity law is an important tool in astronomy because it can be used to determine distances. For example, suppose you find a Cepheid variable in the sky. By measuring its period and using a graph like Figure 22-4, you can determine the star's average luminosity. Knowing the star's average luminosity, you can find out how far away the star must be in order to give the observed brightness. (Box 17-2 explains how this is done.)

Shortly after Leavitt's discovery of the period-luminosity law, Harlow Shapley, a young astronomer at the Mount Wilson Observatory in California, began studying a family of pulsating stars closely related to Cepheid variables called **RR Lyrae variables.** The light curve of an RR Lyrae variable is similar to that of a Cepheid, but RR Lyrae variables have shorter pulsation periods and lower peak luminosities (see Figure 22-4).

The tremendous importance of RR Lyrae variables is that they are commonly found in globular clusters (Figure 22-5). By using the period-luminosity relationship for these stars, Shapley was able to determine the distances to the 93 globular clusters then known. He found that some of them were more than 100,000 light-years from Earth. The large values of these distances immediately suggested that the Galaxy was much larger than Herschel or Kapteyn had thought.

Another striking property of globular clusters is how they are distributed across the sky. Ordinary stars are rather uniformly spread along the Milky Way. However, the majority of the 93 globular clusters that Shapley studied are located in one-half of the sky, widely scattered around the portion of the Milky Way that is in the constellation Sagittarius.

From the directions to the globular clusters and their distances from us, Shapley mapped out the three-dimensional distribution of these clusters in space. In 1920 he concluded that the globular clusters form a huge spherical distribution centered not on Earth but rather about a point in the Milky Way several kiloparsecs away in the direction of Sagittarius (see Figure 22-3b). This point, reasoned Shapley, must coincide with the center of our Galaxy, because of gravitational forces between the disk of the Galaxy and the "halo" of globular clusters. Therefore, by locating the center of the distribution of globular clusters, Shapley was in effect measuring the location of the galactic center.

Modern-Day Measurements

Since Shapley's pioneering observations, many astronomers have measured the distance from the Sun to the **galactic nucleus,** the center of our Galaxy. Shapley's estimate of this distance was too large by about a factor of 2, because he did not take into account the effects of interstellar extinction (which were not well understood at the time). Today, the generally accepted distance to the

VIDEO 22.1 **FIGURE 22-5** R I V U X G
RR Lyrae Variables in a Globular Cluster The arrows point to three RR Lyrae variables in the globular cluster M55, located in the constellation Sagittarius. From the average apparent brightness (as seen in this photograph) and average luminosity (known to be roughly 100 $L_{\odot}$) of these variable stars, astronomers have deduced that the distance to M55 is 6500 pc (20,000 ly). (Harvard-Smithsonian Center for Astrophysics)

galactic nucleus is about 8 kpc (26,000 ly); the actual distance could be greater or less than that value by about 1 kpc (3300 ly).

Just as Copernicus and Galileo showed that Earth was not at the center of the solar system, Shapley and his successors showed that the solar system lies nowhere near the center of the Galaxy. We see that Earth indeed occupies no special position in the universe.

CONCEPTCHECK 22-1

If astronomers observed that globular clusters were evenly spread across all parts of the sky, what would astronomers assume about the location of our Sun and Earth in our Galaxy?

Answer appears at the end of the chapter.

22-2 Observations at nonvisible wavelengths reveal the shape of the Galaxy

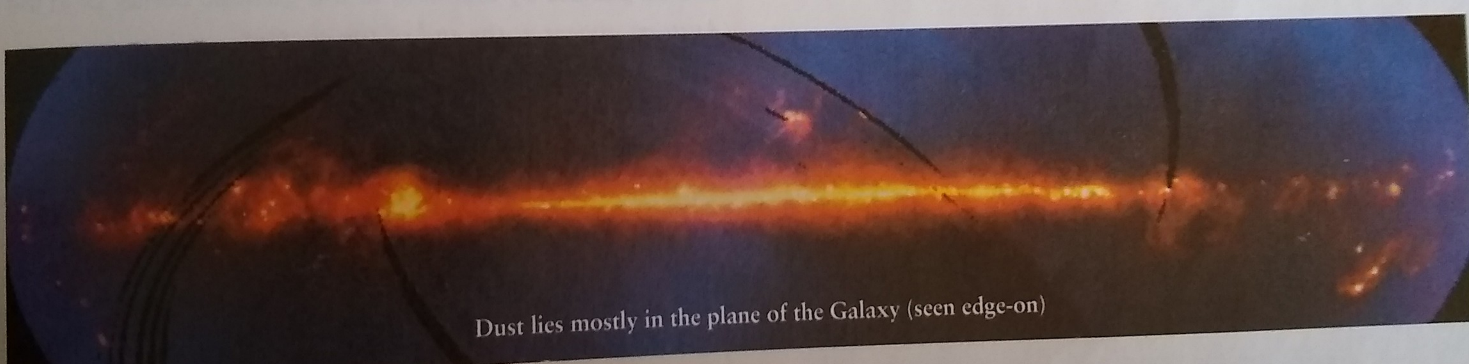
At visible wavelengths, light suffers so much interstellar extinction that the center of the galaxy is totally obscured from view. But the amount of interstellar extinction is roughly inversely proportional to wavelength of light. In other words, the longer the wavelength of light, the farther that light can travel through interstellar dust without being scattered or absorbed. As a result, we can see farther into the plane of the Milky Way at infrared wavelengths than at visible wavelengths, and radio waves can travel all the way through the Galaxy! For this reason, telescopes sensitive to these nonvisible wavelengths are important tools for studying the structure of our Galaxy.

Exploring the Milky Way in the Infrared

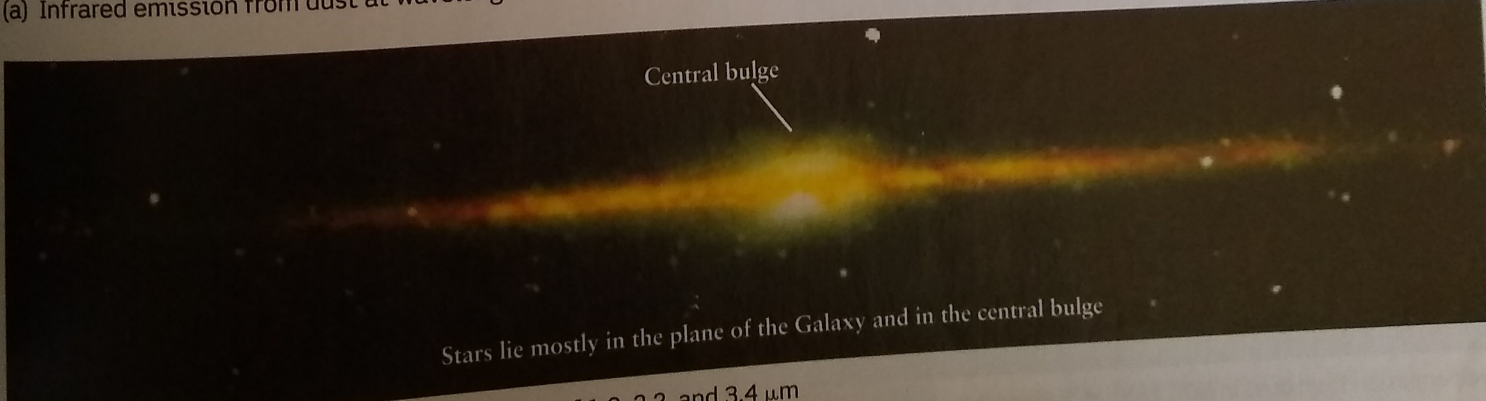
Our Galaxy's dust and stars—including the Sun—lie mostly in a relatively thin disk

Infrared light is particularly useful for tracing the location of interstellar dust in the Galaxy. Starlight warms the dust grains to temperatures in the range of 10 to 90 K; thus, in accordance with Wien's law (see Section 5-4), the dust emits radiation predominately at wavelengths from about 30 to 300 μm. These are called **far-infrared** wavelengths, because they lie in the part of the infrared spectrum most different in wavelength from visible light (see Figure 5-7). At these wavelengths, interstellar dust radiates more strongly than stars, so a far-infrared view of the sky is principally a view of where the dust is. In 1983 the Infrared Astronomical Satellite (IRAS) scanned the sky with a 60-cm reflecting telescope at far-infrared wavelengths, giving the panoramic view of the Milky Way's dust shown in Figure 22-6a.

In 1990 an instrument on the Cosmic Background Explorer (COBE) satellite scanned the sky at **near-infrared** wavelengths that is, relatively short wavelengths closer to the visible spectrum Figure 22-6b shows the resulting near-infrared view of the plan of the Milky Way. At near-infrared wavelengths, interstellar du



(a) Infrared emission from dust at wavelengths of 25, 60, and 100 μm



(b) Infrared emission from dust at wavelengths of 1.2, 2.2, and 3.4 μm

FIGURE 22-6 R I V U X G **The Infrared Milky Way** **(a)** This view was constructed from observations made at far-infrared wavelengths by the IRAS spacecraft. Interstellar dust, which is mostly confined to the plane of the Galaxy, is the principal source of radiation in this wavelength range. **(b)** Observing at near-infrared wavelengths, as in this composite of COBE data, allows us to see much farther throu interstellar dust than we can at visible wavelengths. Light in this wavele range comes mostly from stars in the plane of the Galaxy and in the bu the Galaxy's center. (NASA)

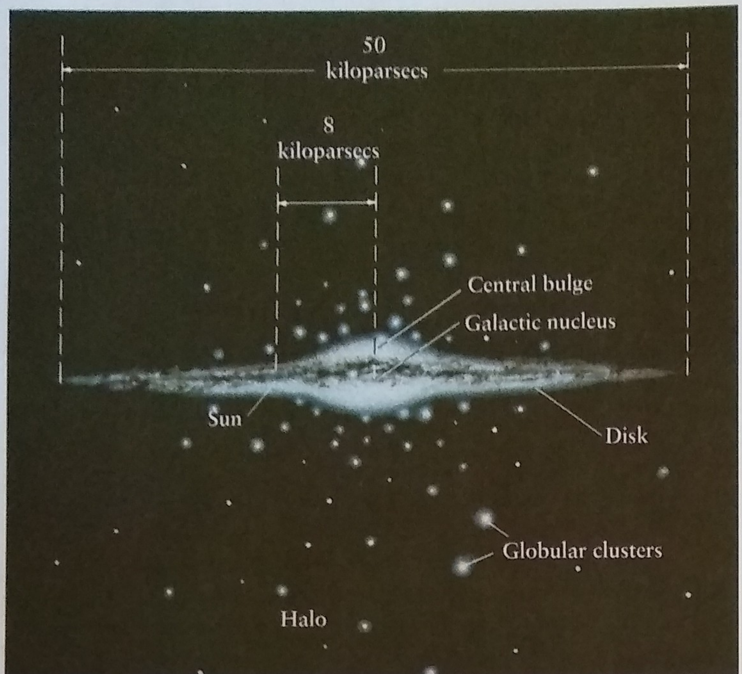


FIGURE 22-7

Our Galaxy (Schematic Edge-on View) There are three major components of our Galaxy: a disk, a central bulge, and a halo. The disk contains gas and dust along with metal-rich (Population I) stars. The halo is composed almost exclusively of old, metal-poor (Population II) stars. The central bulge is a mixture of Population I and Population II stars.

does not emit very much light. Hence, the light sources in Figure 22-6b are stars, which do emit strongly in the near-infrared (especially the cool stars, such as red giants and supergiants). Because interstellar dust causes little interstellar extinction in the near-infrared, many of the stars whose light is recorded in Figure 22-6b lie deep within the Milky Way.

Observations such as those shown in Figure 22-6, along with the known distance to the center of the Galaxy, have helped astronomers establish the dimensions of the Galaxy. The **disk** of our Galaxy is about 50 kpc (160,000 ly) in diameter and about 0.6 kpc (2000 ly) thick, as shown in Figure 22-7. The center of the Galaxy is surrounded by a distribution of stars, called the **central bulge**, which is about 2 kpc (6500 ly) in diameter. This central bulge is clearly visible in Figure 22-6b. The spherical distribution of globular clusters traces the **halo** of the Galaxy.

This structure is not unique to our Milky Way Galaxy. Figure 22-8 shows another galaxy whose dust and stars lie in a disk and that has a central bulge of stars, just like the Milky Way. In the same way that our Sun is a rather ordinary member of the stellar community that makes up the Milky Way, the Milky Way turns out to be a rather common variety of galaxy.

CONCEPTCHECK 22-2

If an astronomer wanted to study the nature of cool stars hiding inside dust clouds, which wavelength would be the best choice, near-infrared (with shorter wavelengths that are nearer to the visible spectrum) or far-infrared (with longer wavelengths farther from the visible spectrum)?

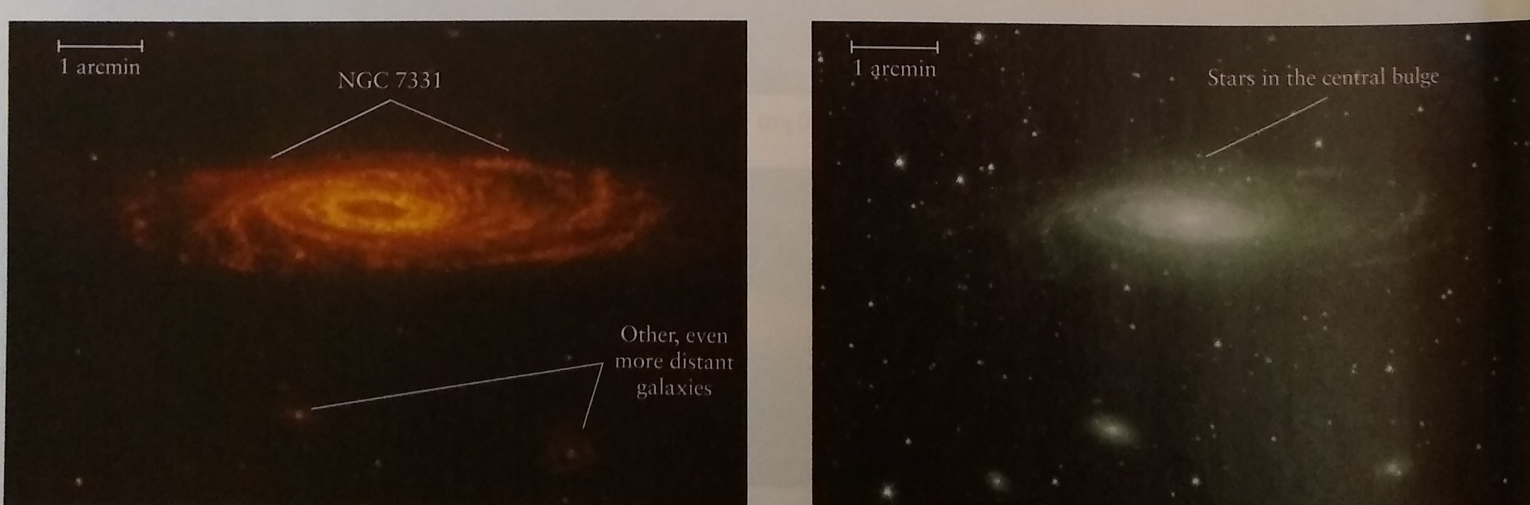
CONCEPTCHECK 22-3

Would an imaginary space traveler have a better view of our Sun and its planets by standing at the galactic center or in the halo?

Answers appear at the end of the chapter.

The Milky Way's Distinct Stellar Populations

It is estimated that our Galaxy contains about 200 billion (2×10^{11}) stars. Remarkably, different kinds of stars are found in the various



(a) Infrared emission from dust in NGC 7331 at 5.8 and 8.0 μm

(b) Infrared emission from stars in NGC 7331 at 3.6 and 4.5 μm

FIGURE 22-8 R I V U X G

NGC 7331: A Near-Twin of the Milky Way If we could view our Galaxy from a great distance, it would probably look like this galaxy in the constellation Pegasus. As in Figure 22-6, the far-infrared image **(a)** reveals the presence of dust in the galaxy's plane, while the near-infrared image **(b)** shows the distribution of stars. These images of NGC 7331, which is about 15 million pc (50 million ly) from Earth, were made with the Spitzer Space Telescope (see Section 6-7, especially Figure 6-26). (NASA; JPL-Caltech; M. Regan [STScI]; and the SINGS Team)

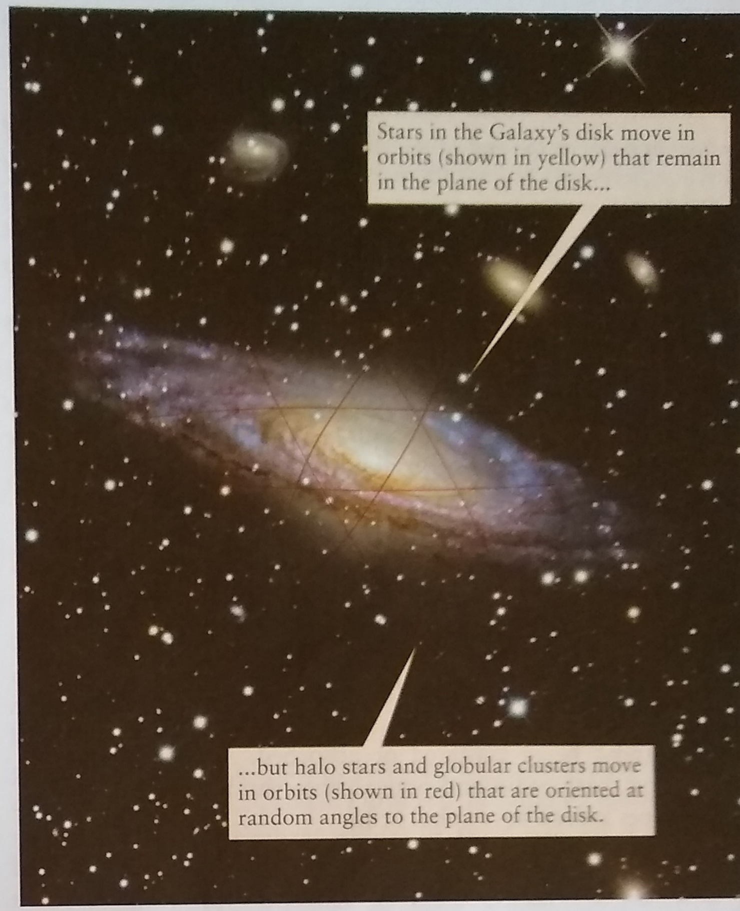


FIGURE 22-9 R I V U X G

Star Orbits in the Milky Way The different populations of stars in our Galaxy travel along different sorts of orbits. The galaxy in this visible-light image is the Milky Way's near-twin NGC 7331, the same galaxy shown at infrared wavelengths in Figure 22-8. (Russell Croman/Science Source)

components of the Galaxy. The globular clusters in the halo are composed of old, metal-poor, Population II stars (see Section 19-5). Although globular clusters are conspicuous, they contain only about 1% of the total number of stars in the halo; most halo stars are single Population II stars in isolation. These ancient stars orbit the Galaxy along paths tilted at random angles to the disk of the Milky Way, as do the globular clusters. By contrast, stars in the disk travel along orbits that remain in the disk (Figure 22-9).

Unlike the halo, the stars in the disk are mostly young, metal-rich, Population I stars like the Sun. The disk of a galaxy like the Milky Way appears bluish because its light is dominated by radiation from hot O and B main-sequence stars. Such stars have very short main-sequence lifetimes (see Section 19-1, especially Table 19-1), so they must be quite young by astronomical standards. Hence, their presence shows that there must be active star formation in the galactic disk. By contrast, no O or B stars are present in the halo, which implies that star formation ceased there long ago.

The central bulge contains *both* Population I stars and metal-poor Population II stars. Since Population II stars are thought to have formed early in the history of the universe, this suggests that some of the stars in the bulge are quite ancient while others were created more recently. The central bulge looks yellowish or reddish because it contains many red giants and red supergiants (see Figure 1-7), but does *not* contain luminous, short-lived, blue O or B stars. Hence, there cannot be ongoing star formation in the central bulge. The same is true for other galaxies whose structure is similar to that of the Milky Way (Figure 22-10).

Why are there such different populations of stars in the halo, disk, and central bulge? Why has star formation stopped in some regions of the Galaxy but continues in other regions? The answers to these questions are related to the way that stars, as well as the gas and dust from which stars form, move within the Galaxy.

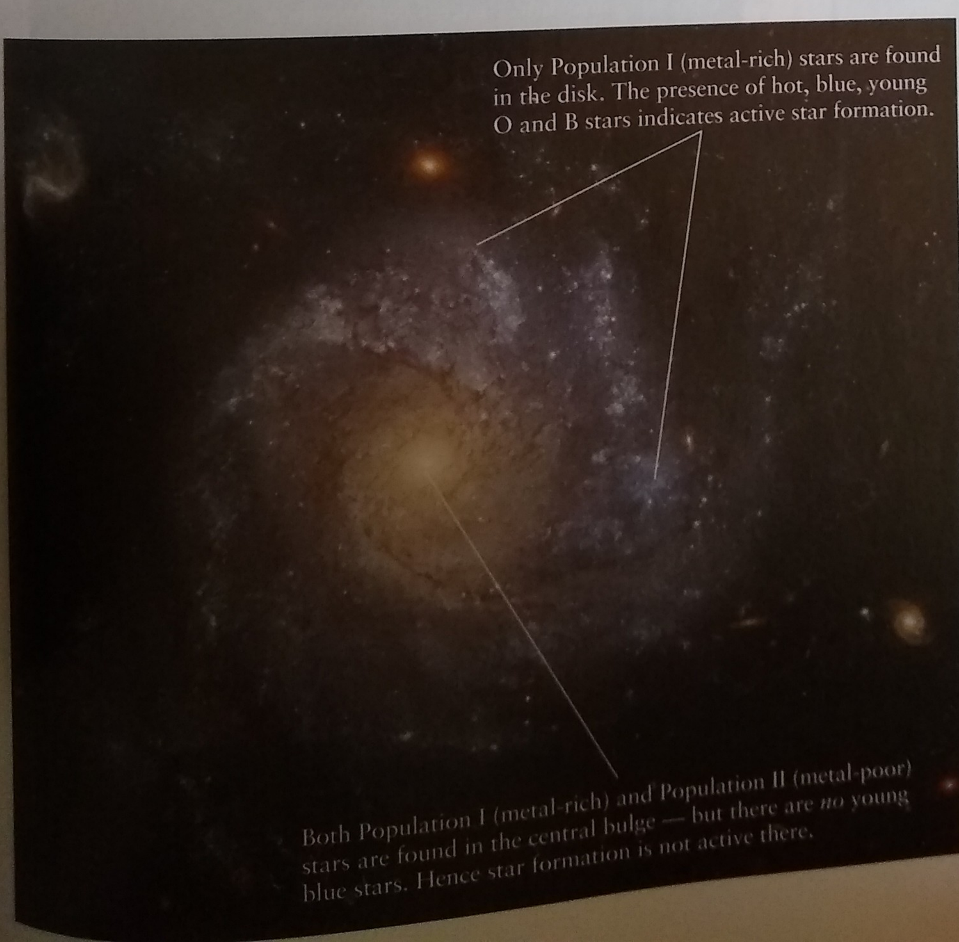


FIGURE 22-10 R I V U X G

Stellar Populations: Disk Versus Central Bulge The disk and central bulge of the Milky Way contain rather different populations of stars. The same is true for the galaxy NGC 1309, which has a similar structure to the Milky Way Galaxy and happens to be oriented face-on to us. NGC 1309 is about 30 million pc (100 million ly) from us in the constellation Eridanus. (NASA, ESA, The Hubble Heritage Team [STScI/AURA] and A. Riess [STScI])

CONCEPTCHECK 22-4

If you were looking to find the most recently formed stars in the Galaxy, where would you most likely look?

Answer appears at the end of the chapter.

22-3 Observations of cold hydrogen clouds and star-forming regions reveal that our Galaxy has spiral arms

The galaxies shown in Figure 22-8 and Figure 22-10 both have **spiral arms,** spiral-shaped concentrations of gas and dust that extend outward from the center in a shape reminiscent of a pinwheel. Assuming our Galaxy is similar to other galaxies, observations of spiral arms would lead us to suspect that our own Milky Way Galaxy has this feature. However, because interstellar dust obscures our visible-light view in the pancakelike plane of our Galaxy, a detailed understanding of the structure of our galactic disk had to wait until the development of radio astronomy. Thanks to their long wavelengths, radio waves can penetrate the interstellar medium even more easily than infrared light and can travel without being scattered or absorbed. As we shall see in this section, both radio and optical observations reveal that our Galaxy does indeed have spiral arms.

Mapping Hydrogen in the Milky Way

LOOKING DEEPER 22.1

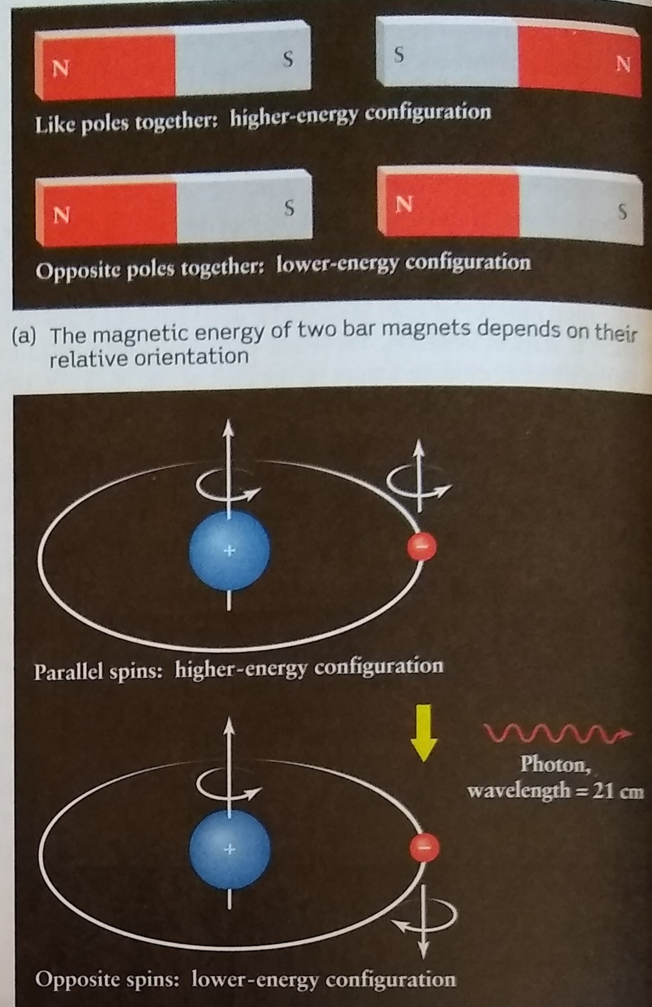
Our Galaxy's dust and stars—including the Sun—lie mostly in a relatively thin disk

Hydrogen is by far the most abundant element in the universe (see Figure 8-4 in Section 8-2). Hence, by looking for concentrations of hydrogen gas, we should be able to detect important clues about the distribution of matter in our Galaxy. Unfortunately, ordinary visible-light telescopes are of little use in this quest, because hydrogen atoms can only emit visible light if they are first excited to high energy levels (see Section 5-8, and especially Figure 5-24). This excitation is quite unlikely to occur in the cold depths of interstellar space. Furthermore, even if there are some hydrogen atoms that glow strongly at visible wavelengths, interstellar extinction due to dust (see Section 22-1) would make it impossible to see this glow from distant parts of the Galaxy.

What makes it possible to map out the distribution of hydrogen in our Galaxy is that even cold hydrogen clouds emit *radio* waves. As we saw in Section 22-2, radio waves can easily penetrate the interstellar medium, so we can detect the radio emission from such cold clouds no matter where in the Galaxy they lie. The hydrogen in these clouds is neutral—that is, not ionized—and is called H I. (This distinguishes it from ionized hydrogen, which is designated H II.) To understand how H I clouds can emit radio waves, we must probe a bit more deeply into the structure of protons and electrons, the particles of which hydrogen atoms are made.

In addition to having mass and charge, particles such as protons and electrons possess a tiny amount of angular momentum (that is, rotational motion) commonly called **spin.** Very roughly, you can visualize a proton or electron as a tiny, electrically charged sphere that spins on its axis. Because electric charges in motion generate magnetic fields, a proton or electron behaves like a tiny magnet with a north pole and a south pole (Figure 22-11).

If you have ever played with magnets, you know that two magnets attract when the north pole of one magnet is next to the south pole of the other and repel when two like poles (both north or both south) are next to each other (Figure 22-11a). This behavior can also be described in terms of magnetic energy: The energy of the two magnets is least when opposite poles are together and highest



(a) The magnetic energy of two bar magnets depends on their relative orientation

(b) The magnetic energy of a proton and electron depends on the relative spin orientation

FIGURE 22-11

Magnetic Interactions in the Hydrogen Atom (a) The energy of a pair of magnets is high when their north poles or their south poles are near each other, and low when they have opposite poles near each other. (b) Thanks to their spin, electrons and protons are both tiny magnets. When the electron flips from the higher-energy configuration (with its spin in the same direction as the proton's spin) to the lower-energy configuration (with its spin opposite to the proton's spin), the atom loses a tiny amount of energy and emits a radio photon with a wavelength of 21 cm.

nen like poles are together. Hence, as shown in Figure 22-11b, e energy of a hydrogen atom is slightly different depending on hether the spins of the proton and electron are in the same direcon or opposite directions. (According to the laws of quantum echanics, these are the only two possibilities; the spins cannot be random angles.)

If the spin of the electron changes its orientation from the gher-energy configuration to the lower-energy one—called a **spin-ip transition**—a photon is emitted. The energy difference between ne two spin configurations is very small, only about 10^{-6} as great as nose between different electron orbits (see Figure 5-24). Therefore, ne photon emitted in a spin-flip transition between these configuraons has only a small energy, and thus its wavelength is a relatively ong 21 cm—a radio wavelength. These spin-flip transitions occur pontaneously in our Milky Way's diffuse hydrogen gas, which llows the possibility of mapping hydrogen through this method.

The spin-flip transition in neutral hydrogen was first predicted n 1944 by the Dutch astronomer Hendrik van de Hulst. His calculations suggested that it should be possible to detect the **21-cm radio emission** from interstellar hydrogen, although a very sensiive radio telescope would be required. In 1951, Harold Ewen and Edward Purcell at Harvard University first succeeded in detecting this faint emission from hydrogen between the stars.

Figure 22-12 shows the results of a more recent 21-cm survey of the entire sky. Neutral hydrogen gas (H I) in the plane of the Milky Way stands out prominently as a bright band across the middle of this image.

The distribution of gas in the Milky Way is not uniform but is actually quite frothy. In fact, our Sun lies near the edge of an irregularly shaped region within which the interstellar medium is very thin but at very high temperatures (about 10^6 K, but so thin it would feel cold). This region, called the **Local Bubble**, is several hundred parsecs across. The Local Bubble may have been carved out by a supernova that exploded nearby some 300,000 years ago.

Remarkably, spin-flip transitions are used not only to map our Galaxy but also to map the internal structure of the human body. Box 22-1 discusses this application, called magnetic resonance imaging.

CONCEPTCHECK 22-5

If a spin-flip transition released substantially more energy, such that a photon was emitted in the far-infrared range, would the Milky Way stretching across the night sky appear brighter or dimmer?

CALCULATIONCHECK 22-1

If a 21-cm photon is observed when a single hydrogen atom undergoes a spin-flip transition, what wavelength is observed when 10 hydrogen atoms undergo spin-flip transitions?

Answers appear at the end of the chapter.

Detecting Our Galaxy's Spiral Arms

The detection of 21-cm radio emission was a major breakthrough that permitted astronomers to reveal the presence of spiral arms in the galactic disk. Figure 22-13 shows how spiral arms were detected. Suppose that you aim a radio telescope along a particular line of sight across the Galaxy. Your radio receiver, located at *S* (the position of the solar system), picks up 21-cm emission from H I clouds at points 1, 2, 3, and 4. However, the radio waves from these various clouds are Doppler shifted by slightly different amounts, because the clouds are moving at different speeds as they travel with the rotating Galaxy.

It is important to remember that the Doppler shift reveals only motion along the line of sight (review Figure 5-26). In Figure 22-13, cloud 2 has the highest speed along our line of sight, because it is moving directly toward us. Consequently, the radio waves from cloud 2 exhibit a larger Doppler shift than those from the other three clouds along our line of sight. Because clouds 1 and 3 are at the same distance from the galactic center, they have the same orbital speed. The fraction of their velocity parallel to our line of sight is also the same, so their radio waves exhibit the

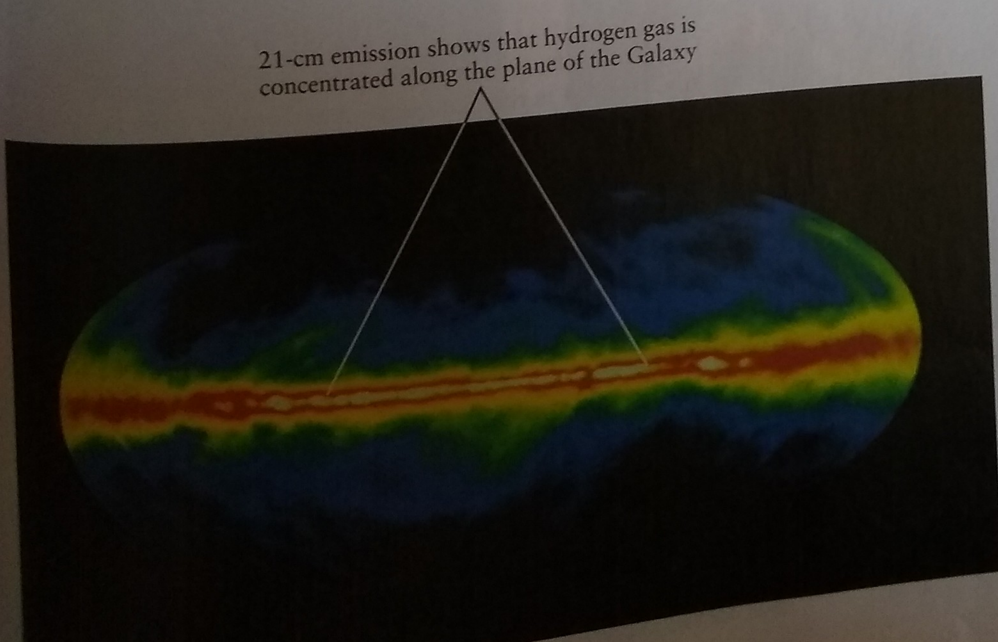


FIGURE 22-12 R I V U X G **The Sky at 21 Centimeters** This image was made by mapping the sky with radio telescopes tuned to the 21-cm wavelength emitted by neutral interstellar hydrogen (H I). The entire sky has been mapped onto an oval, and the plane of the Galaxy extends horizontally across the image as in Figure 22-6. Black and blue represent the weakest emission, and red and white the strongest. (Courtesy of C. Jones and W. Forman, Harvard-Smithsonian Center for Astrophysics)

BOX 22-1 ASTRONOMY DOWN TO EARTH

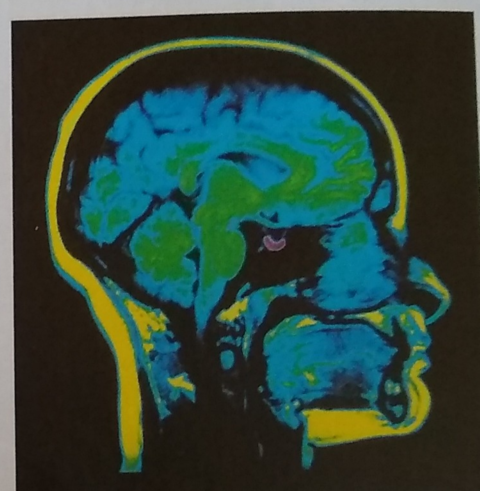
Spin-Flip Transitions in Medicine

Thanks to their spin, protons and electrons act like microscopic bar magnets. In a hydrogen atom, the interaction between the magnetism of the electron and that of the proton gives rise to the 21-cm radio emission. But these particles can also interact with outside magnetic fields, such as that produced by a large electromagnet. This physical principle is behind **magnetic resonance imaging,** an important diagnostic tool of modern medicine.

Much of the human body is made of water. Every water molecule has two hydrogen atoms, each of which has a nucleus made of a single proton. If a person's body is placed in a strong magnetic field, the spins of the protons in the hydrogen atoms of their body can either be in the same direction as the field ("aligned") or in the direction opposite to the field ("opposed"). The aligned orientation has lower energy, and therefore the majority of protons end up with their spins in this orientation. But if a radio wave of just the right wavelength is now sent through the person's body, an aligned proton can absorb a radio photon and flip its spin into the higher-energy, opposed orientation. How much of the radio wave is absorbed depends on the number of protons in the body, which in turns depends on how much water (and, thus, how much water-containing tissue) is in the body.

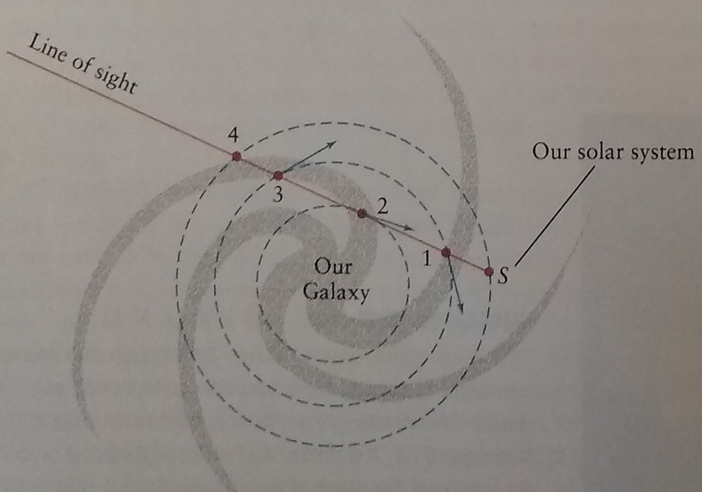
In magnetic resonance imaging, a magnetic field is used whose strength varies from place to place. The difference in energy between the opposed and aligned orientations of a proton depends on the strength of the magnetic field, so radio waves will only be absorbed at places where this energy difference is equal to the energy of a radio photon. (This equality is called *resonance,* which is how magnetic resonance imaging gets its name.) By varying the magnetic field strength over the body and the wavelength of the radio waves, and by measuring how much of the radio wave is absorbed by different parts of the body, it is possible to map out the body's tissues. The accompanying false-color image shows such a map of a patient's head.

Unlike X-ray images, which show only the densest parts of the body, such as bones and teeth, magnetic resonance imaging can be used to view less dense (but water-containing) soft tissue. Just as the 21-cm radio emission has given astronomers a clear view of what were hidden regions of our Galaxy, magnetic resonance imaging allows modern medicine to see otherwise invisible parts of the human body.



R I V U X G

(Scott Camazine/Science Source)



• Hydrogen clouds 1 and 3 are approaching us: They have a moderate blueshift.

• Hydrogen cloud 2 is approaching us at a faster speed: It has a larger blueshift.

same Doppler shift, which is less than the Doppler shift of clou 2. Finally, cloud 4 is the same distance from the galactic center the Sun. This cloud is thus orbiting the Galaxy at the same spe as the Sun, resulting in no net motion along the line of sight. Rad waves from cloud 4, as well as from hydrogen gas near the Su are not Doppler shifted at all.

These various Doppler shifts cause radio waves from gases different parts of the Galaxy to arrive at our radio telescopes w wavelengths slightly different from 21 cm. It is therefore possi

FIGURE 22-13

A Technique for Mapping Our Galaxy If we look within the plane of our Galaxy from our position at *S*, hydrogen clouds at different location (shown as 1, 2, 3, and 4) along our line of sight are moving at slightly diffe speeds relative to us. As a result, radio waves from these various gas clouds are subjected to slightly different Doppler shifts. This permits radio astronomers to sort out the gas clouds and thus map the Galaxy.

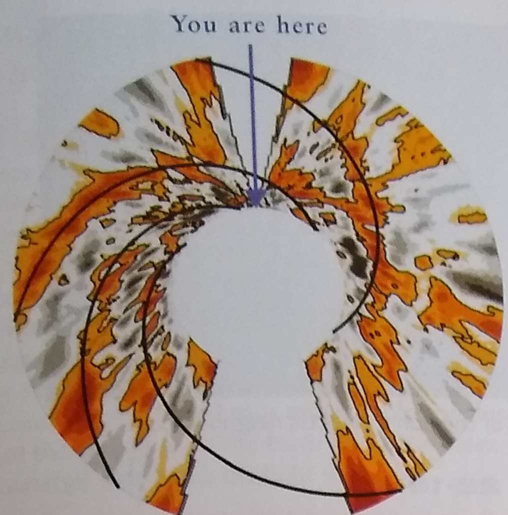


FIGURE 22-14 R I V U X G

A Map of Neutral Hydrogen in Our Galaxy This map, constructed from radio-telescope surveys of 21-cm radiation, shows the distribution of hydrogen gas in a reconstructed (or hypothetical) face-on view of our Galaxy. The map suggests a spiral structure. Details in the blank, wedge-shaped region at the bottom of the map are unknown. Gas in this part of the Galaxy is moving perpendicular to our line of sight and thus does not exhibit a detectable Doppler shift. (Image courtesy of Leo Blitz, Ph.D.)

to sort out the various gas clouds and thus produce a map of the Galaxy like that shown in Figure 22-14.

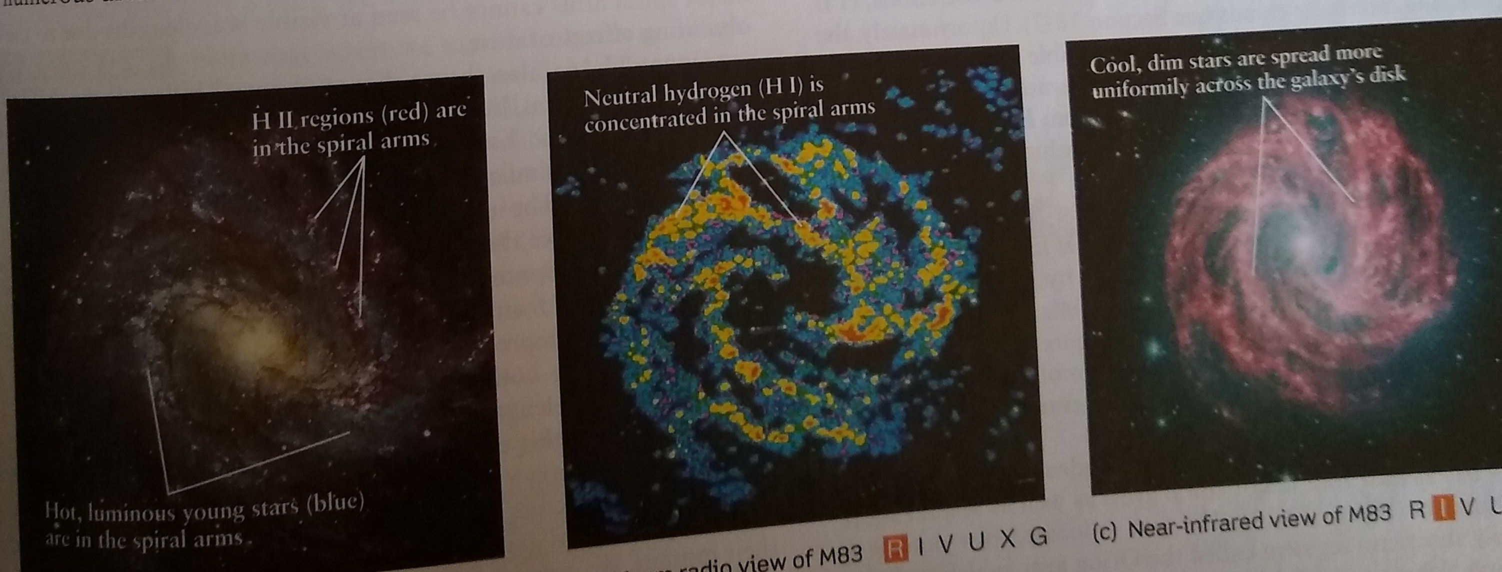
Figure 22-14 shows that neutral hydrogen gas is not spread uniformly around the disk of the Galaxy but is concentrated into numerous arched lanes. Similar features are seen in other galaxies beyond the Milky Way. Unlike the view from within our own Galaxy, we can view other galaxies face-on to easily see their distribution of stars, gas, and dust. As an example, the galaxy in Figure 22-15a has prominent spiral arms outlined by hot, luminous, blue main-sequence stars and the red emission nebulae (H II regions) found near many such stars. Stars of this sort are very short-lived, so these features indicate that spiral arms are sites of active, ongoing star formation. The 21-cm radio image of this same galaxy, shown in Figure 22-15b, shows that spiral arms are also regions where neutral hydrogen gas is concentrated, similar to the structures in our own Galaxy visible in Figure 22-14. This similarity is a strong indication that our Galaxy also has spiral arms.

CAUTION! Photographs such as Figure 22-15a can lead to the impression that there are very few stars between the spiral arms of a galaxy. Nothing could be further from the truth! In fact, stars are distributed rather uniformly throughout the disk of a galaxy like the one in Figure 22-15a; the density of stars in the spiral arms is only about 5% higher than in the rest of the disk. The spiral arms stand out nonetheless because they are where hot, blue O and B stars are found. One such star is about 10^4 times more luminous than an average star in the disk, so the light from O and B stars completely dominates the visible appearance of a spiral galaxy.

CONCEPTCHECK 22-6

When looking at neutral hydrogen gas that is moving away from you, how is its wavelength changed as compared to neutral hydrogen gas that is not moving relative to you?

Answer appears at the end of the chapter.



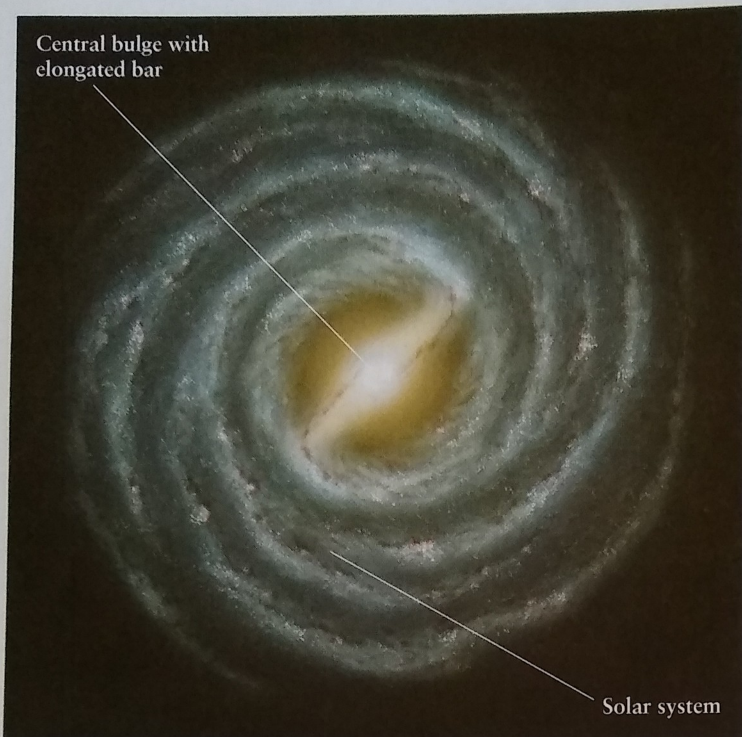
(a) Visible-light view of M83 R I V U X G

(b) 21-cm radio view of M83 R I V U X G

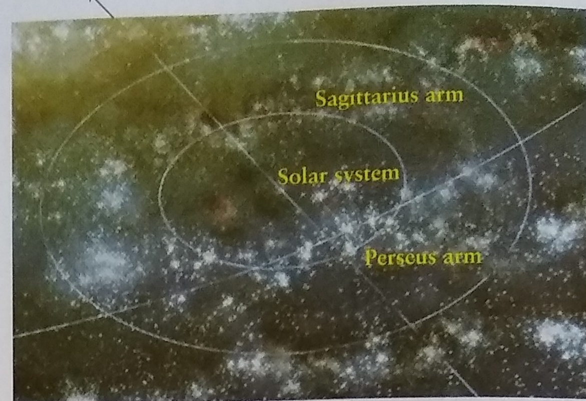
(c) Near-infrared view of M83 R I V U

FIGURE 22-15

A Spiral Galaxy The galaxy M83 lies in the southern constellation Hydra about 5 million pc (15 million ly) from Earth. **(a)** This visible-light image clearly shows the spiral arms. The presence of young stars and H II regions indicates that star formation takes place in spiral arms. **(b)** This radio view at a wavelength of 21 cm shows the emission from neutral interstellar hydrogen gas (H I). Note that essentially the same pattern of spiral arms is traced out in image as in the visible-light photograph. **(c)** M83 has a different appearan this near-infrared view. The starlight has been removed in this image to re the infrared emission of dust throughout the galaxy. (a: ©Australian Astronor Observatory/David Malin Images; b: VLA, NRAO; c: NASA/JPL-Caltech)



(a) The structure of the Milky Way's disk



(b) Closeup of the Sun's galactic neighborhood

FIGURE 22-16

Our Galaxy Seen Face-on: Artist's Impressions **(a)** The Galaxy's diameter is about 50,000 pc (160,000 ly), and our solar system is about 8000 pc (26,000 ly) from the galactic center. The elongated central bulge is about 8300 pc (27,000 ly) long and is oriented at approximately 45° to a lin running from the solar system to the galactic center. **(b)** Our solar system is located between the Sagittarius and Perseus arms, two of the major spiral arms in the Milky Way. (a: NASA/JPL-Caltech/R. Hurt, SSC; b: NG Maps/National Geographic Creative)

Mapping the Spiral Arms and the Central Bulge

Figure 22-15a suggests that we can confirm the presence of spiral structure in our own Galaxy by mapping the locations of star-forming regions. Such regions are marked by OB associations, H II regions, and molecular clouds (see Section 18-7). Unfortunately, the first two of these are best observed using visible light, and interstellar extinction limits the range of visual observations in the plane of the Galaxy to less than 3 kpc (10,000 ly) from Earth. But there are enough OB associations and H II regions within this range to plot the spiral arms in the vicinity of the Sun.

Molecular clouds are easier to observe at great distances, because molecules of carbon monoxide (CO) in these clouds emit radio waves that are relatively unaffected by interstellar extinction. Hence, the positions of molecular clouds have been plotted even in remote regions of the Galaxy, as Figure 18-21 shows. (We saw in Section 18-7 that CO molecules in molecular clouds emit more strongly than the hydrogen atoms do, even though hydrogen is the principal constituent of these clouds.)

Taken together, all these observations demonstrate that our Galaxy has at least four major spiral arms as well as several short arm segments (Figure 22-16). The Sun is located just outside a relatively short arm segment called the Orion arm, which includes the Orion Nebula and neighboring sites of vigorous star formation in that constellation.

Two major spiral arms border either side of the Sun's position. The Sagittarius arm is on the side toward the galactic center. You see this arm on June and July nights when you look at the portion of the Milky Way stretching across Scorpius and Sagittarius, near the center of the upper photograph that opens this chap In December and January, when our nighttime view is direc away from the galactic center, we see the Perseus arm. The o major spiral arms cannot be seen at visible wavelengths due to obscuring effects of dust.

Figure 22-16a also shows that the central bulge of the M Way is not spherical, but is elongated like a bar. The Milky W bulge is unlike the bulge of the galaxy NGC 7331 shown Figure 22-8, but similar to the bulge of the galaxy M83 sh in Figure 22-15. The elongated shape of the central bulge been suspected since the 1980s; this shape was confirmed in 2 using the Spitzer Space Telescope, which was used to survey infrared emissions from some 3 million stars in the central b Thus, the artist's impression shown in Figure 22-16a is base observations using both radio wavelengths (for the spiral a and infrared wavelengths (for the central bulge). We will s Section 22-5 that this elongated shape may play a crucial ro sustaining the Galaxy's spiral structure.

To get a full picture of our Galaxy, you need to know not where our stars and gas are located, but you must also unders their motion. We now look at the rotational motion of our Ga and how it reveals one of the greatest mysteries in all of scien dark matter.

CONCEPTCHECK 22-7

If you traveled from Earth in a direction *away* from the cent the Galaxy, what is the first major arm you would reach?

Answer appears at the end of the chapter.