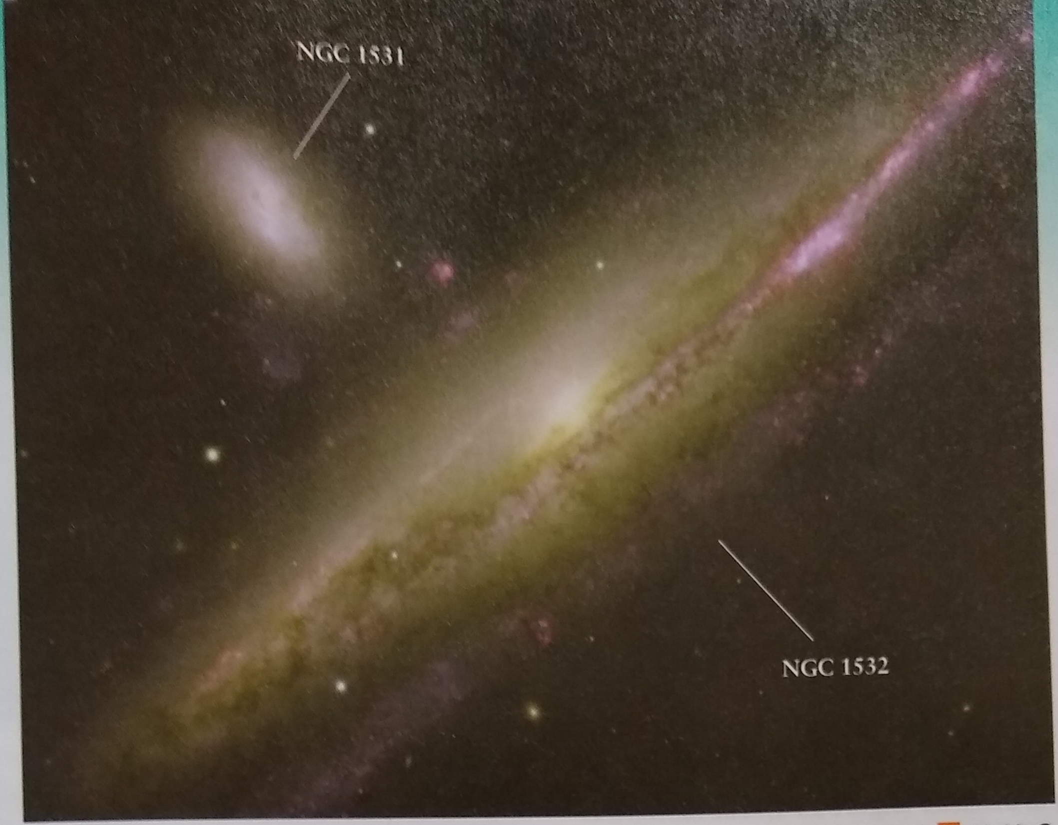


R I V U X G

The two galaxies NGC 1531 and NGC 1532 are so close together that they exert strong gravitational forces on each other. Both galaxies are about 17 million pc (55 million ly) from us in the constellation Eridanus. (Gemini Observatory/Travis Rector, University of Alaska, Anchorage)

CHAPTER
23

Galaxies

EARNING GOALS

By reading the sections of this chapter, you will learn

23-1 How astronomers first observed other galaxies
23-2 How astronomers determined the distances to other galaxies
23-3 The basic types of galaxies
23-4 What techniques astronomers use to determine distances to remote galaxies
23-5 How the velocities of remote galaxies tell us that the universe is expanding
23-6 How galaxies are grouped into clusters and larger structures
23-7 What happens when galaxies collide
23-8 What observations indicate the presence of dark matter in other galaxies and clusters
23-9 How galaxies formed and evolved

A century ago, most astronomers thought that the entire universe was only a few thousand light-years across and that nothing lay beyond our Milky Way Galaxy. One of the most important discoveries of the twentieth century was that this conception was utterly wrong. We now understand that the Milky Way is just one of billions of galaxies strewn across billions of light-years. The accompanying image shows two of them, denoted by rather mundane catalog numbers (NGC 1531 and NGC 1532) that give no hint to these galaxies' magnificence.

Some galaxies are spirals like NGC 1532 or the Milky Way, with arching spiral arms that are active sites of star formation. (The bright pink bands in NGC 1532 are H II regions, clouds of excited hydrogen that are set aglow by ultraviolet radiation from freshly formed massive stars.) Others, like NGC 1531, are featureless, ellipse-shaped agglomerations of stars, virtually devoid of interstellar gas and dust. Some galaxies are only one one-hundredth the size and one ten-thousandth the mass of the Milky Way. Others are giants, with 5 times the size and 50 times the mass of the Milky Way. Only about 10% of a typical galaxy's mass emits radiation of any kind; the remainder is made up of the mysterious dark matter.

Just as most stars are found within galaxies, most galaxies are located in groups and clusters. These clusters of galaxies stretch across the universe, forming huge, lacy patterns. Remarkably, remote clusters of galaxies are receding from us; the greater their distance, the more rapidly they are moving away. This relationship between distance and recessional velocity, called the Hubble law, reveals that our immense universe is expanding. In Chapters 25 and 26 we will learn what this implies about the distant past and remote future of the universe.

23-1 When galaxies were first discovered, it was not clear that they lie far beyond the Milky Way

As early as 1755, the German philosopher Immanuel Kant suggested that vast collections of stars lie outside the confines of the Milky Way. Less than a century later, an Irish astronomer observed the structure of some of the "island universes" that Kant proposed.

William Parsons, the third Earl of Rosse, was a wealthy amateur astronomer who used his fortune to build immense telescopes. His largest telescope, completed in February 1845, had an objective mirror 1.8 meters (6 feet) in diameter (Figure 23-1). The mirror was mounted at one end of a 60-foot tube controlled by cables, straps, pulleys, and cranes (Figure 23-1a). For many years, this triumph of nineteenth-century engineering was the largest telescope in the world.

> As late as the 1920s it was unclear whether spiral nebulae were very remote "island universes" or simply nearby parts of our Galaxy

With this new telescope, Rosse examined many of the nebulae that had been discovered and cataloged by William Herschel. He observed that some of these nebulae have a distinct spiral structure. One of the best examples is M51, also called NGC 5194. (The "M" designations of galaxies and nebulae come from a catalog compiled by the French astronomer Charles Messier between 1758 and 1782. The "NGC" designations come from the much more extensive "New General Catalogue" of galaxies and nebulae published in 1888 by J. L. E. Dreyer, a Danish astronomer who lived and worked in Ireland.)

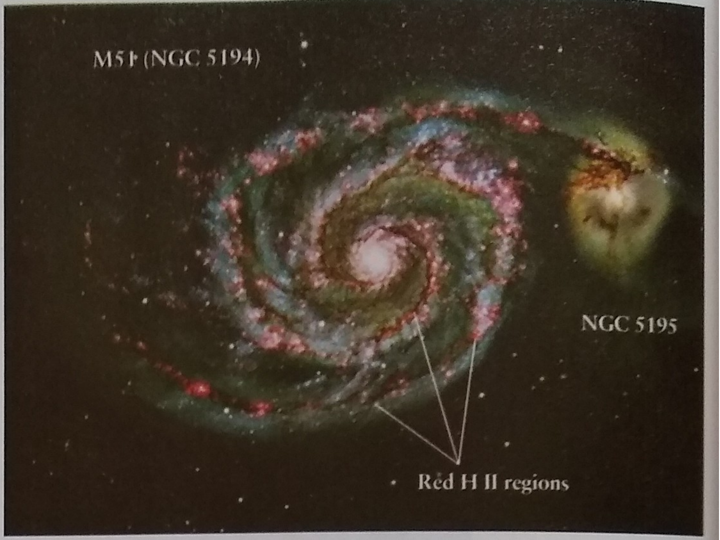
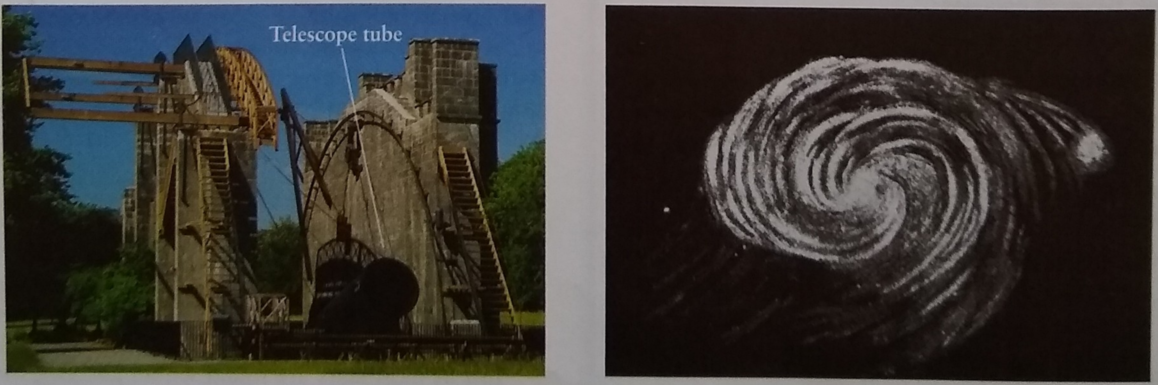


FIGURE 23-2 R I **V** U X G
A Modern View of the Spiral Galaxy M51 This galaxy, also called NGC 5194, has spiral arms that are outlined by glowing H II regions. These regions reveal the sites of star formation (see Section 18-2). One spiral arm extends toward the companion galaxy NGC 5195. (CFHT)

Lacking photographic equipment, Lord Rosse had to make drawings of what he saw. Figure 23-1b shows a drawing he made of M51, which compares favorably with modern photographs, as shown in Figure 23-2. Views such as this inspired Lord Rosse to echo Kant's proposal that such nebulae are actually "island universes."

Many astronomers of the nineteenth century disagreed with this notion of island universes. A considerable number of nebulae are in fact scattered throughout the Milky Way. (Figures 18-2



(a) Rosse's "Leviathan of Parsonstown"

(b) M51 as viewed through the "Leviathan"

FIGURE 23-1 R I **V** U X G
A Pioneering View of Another Galaxy **(a)** Built in 1845, this structure housed the largest telescope of its day. The telescope itself (the black cylinder pointing at a 45° angle above the horizontal) was restored to its original state during 1996–1998. **(b)** Using his telescope, Lord Rosse made this sketch of spiral structure in M51. This galaxy, whose angular size is 8 × 11 arcminutes (about a third the angular size of the full moon), is today called the Whirlpool Galaxy because of its distinctive appearance. (a: Richard T. Nowitz/Corbis)

nd 18-4 show some examples.) The safest assumption was that spiral nebulae," even though they are very different in shape from ther sorts of nebulae, could also be components of our Galaxy.

The astronomical community became increasingly divided ver the nature of the spiral nebulae. In April 1920, two oppos-ng ideas were presented before the National Academy of Sciences n Washington, D.C. On one side was Harlow Shapley from the Mount Wilson Observatory, renowned for his recent determi-ation of the size of the Milky Way Galaxy (see Section 22-1). Shapley thought the spiral nebulae were relatively small, nearby objects scattered around our Galaxy like the globular clusters he had studied. Opposing Shapley was Heber D. Curtis of the University of California's Lick Observatory. Curtis championed the island universe theory, arguing that each of these spiral nebulae is a rotating system of stars much like our own Galaxy.

The Shapley-Curtis "debate" generated much heat but little light. Nothing was decided, because no one could present conclusive evidence to demonstrate exactly how far away the spiral nebulae are. Astronomy desperately needed a definitive determination of the distance to a spiral nebula. Such a measurement became the first great achievement of a young man who studied astronomy at the Yerkes Observatory, near Chicago. His name was Edwin Hubble.

CONCEPTCHECK 23-1

If you were observing one of the "spiral nebulae" and determined that it was closer than some of the stars of our Galaxy, would you be providing evidence in support of Shapley's argument or Curtis's argument?

Answer appears at the end of the chapter.

23-2 Hubble proved that the spiral nebulae are far beyond the Milky Way

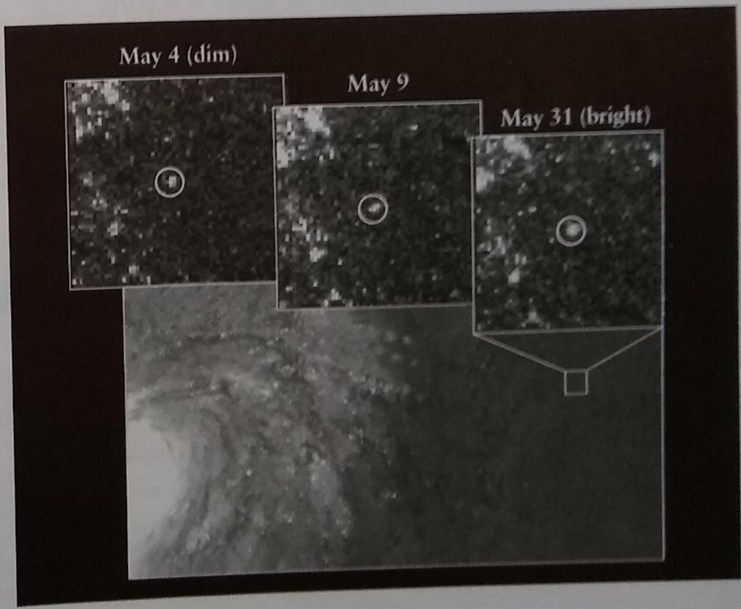
After completing his studies, Edwin Hubble joined the staff of the Mount Wilson Observatory in Pasadena, California. On October 6, 1923, he took an historic photograph of the Andromeda "Nebula," one of the spiral nebulae around which controversy raged. (Figure 23-3 is a modern photograph of this object.)

Hubble carefully examined his photographic plate and discovered a *new* bright spot—what he at first thought to be a nova. Referring to previous plates of that region, he soon realized that the object was actually a Cepheid variable star. Further scrutiny of additional plates over the next several months revealed several more Cepheids. Figure 23-4 shows modern observations of a Cepheid in another "spiral nebula."

Just as RR Lyrae variable stars demonstrated the extent of the Milky Way, Cepheid variables revealed the immense distances to other galaxies

As we saw in Section 19-6, Cepheid variables help astronomers determine distances. An astronomer begins by carefully measuring the variations in apparent brightness of a Cepheid variable, then recording the results in the form of a plot of brightness versus time, or light curve (see Figure 19-18a). This graph gives the variable star's period and average brightness. Given the star's period,

FIGURE 23-3 R I **V** U X G
The Andromeda Galaxy Also known as M31, the Andromeda Galaxy can be seen with a small telescope, or even the naked eye on a clear night. Edwin Hubble was the first to demonstrate that M31 is actually a galaxy that lies far beyond the Milky Way. M31 is the largest galactic neighbor near our Milky Way. A collision between our Milky Way and the Andromeda Galaxy is expected in about 3.75 billion years. M32 and M110 are two small satellite galaxies that orbit M31. (Science Source)



VIDEO 23.1

FIGURE 23-4 R I **V** U X G
Measuring Galaxy Distances with Cepheid Variables By observing Cepheid variable stars in M100, the galaxy shown here, astronomers have found that it is about 17 Mpc (56 million ly) from Earth. The insets show on of the Cepheids in M100 at different stages in its brightness cycle, which lasts several weeks. (Wendy L. Freedman, Carnegie Institution of Washington, and NASA)

BOX 23-1 TOOLS OF THE ASTRONOMER'S TRADE

Cepheids and Supernovae as Indicators of Distance

Because their periods are directly linked to their luminosities, Cepheid variables are one of the most reliable tools astronomers have for determining the distances to galaxies. To this day, astronomers use this link—much as Hubble did back in the 1920s—to measure intergalactic distances. More recently, they have begun to use Type Ia supernovae, which are far more luminous and thus can be seen much farther away, to determine the distances to very remote galaxies.

EXAMPLE: In 1992 a team of astronomers observed Cepheid variables in a galaxy called IC 4182 to deduce this galaxy's distance from Earth. One such Cepheid has a period of 42.0 days and an average apparent magnitude (m) of +22.0. (See Box 17-3 for an explanation of the apparent magnitude scale.) By comparison, the dimmest star you can see with the naked eye has $m = +6$; this Cepheid in IC 4182 appears less than one one-millionth as bright.

According to the period-luminosity relation shown in Figure 19-20, such a Cepheid with a period of 42.0 days has an average luminosity of 33,000 $L_{\odot}$. An equivalent statement is that this Cepheid has an average absolute magnitude (M) of –6.5. (This compares to $M = +4.8$ for the Sun.) Use this information to determine the distance to IC 4182.

Situation: We are given the apparent magnitude $m = +22.0$ and the absolute magnitude $M = -6.5$ of the Cepheid variable star in IC 4182. Our goal is to calculate the distance to this star, and hence the distance to the galaxy of which it is part.

Tools: We use the relationship between apparent magnitude, absolute magnitude, and distance given in Box 17-3.

Answer: In Box 17-3, we saw that the apparent magnitude of a star is related to its absolute magnitude and distance in parsecs (d) by

$$m - M = 5 \log d - 5$$

This equation can be rewritten as

$$d = 10^{(m - M + 5)/5} \text{ parsecs}$$

We have $m - M = (+22.0) - (-6.5) = 22.0 + 6.5 = 28.5$. (Recall from Box 17-3 that $m - M$ is called the *distance modulus*.) Hence, our equation becomes

$$d = 10^{(28.5 + 5)/5} \text{ parsecs} = 10^{6.7} \text{ parsecs} = 5 \times 10^{6} \text{ parsecs}$$

(A calculator is needed to calculate the quantity $10^{6.7}$.)

Review: Our result tells us that the galaxy is 5 million parcsecs, or 5 Mpc, from Earth (1 Mpc = 10^6 pc). This distance can also be expressed as 16 million light-years.

EXAMPLE: Astronomers are interested in IC 4182 because a Type Ia supernova was observed there in 1937. All Type Ia supernovae are exploding white dwarfs that reach nearly the same maximum brightness at the peak of their outburst (see Section 20-9). Once astronomers know the peak absolute magnitude of Type Ia supernovae, they can use these supernovae as distance indicators. Because the distance to IC 4182 is known from its Cepheids, the 1937 observations of the supernova in that galaxy help us calibrate Type Ia supernovae as distance indicators.

At maximum brightness, the 1937 supernova reached an apparent magnitude of $m = +8.6$. What was its absolute magnitude at maximum brightness?

Situation: We are given the supernova's apparent magnitude m, and we know its distance from the previous example. Our goal is to calculate its absolute magnitude M.

Tools: We again use the relationship $m - M = 5 \log d - 5$.

Answer: We could plug in the value of d found in the previous example. But it is simpler to note that the distance modulus $m - M$ has the same value no matter whether it refers to a Cepheid, a supernova, or any other object, just so it is at the same distance d. From the Cepheid example we have $m - M = 28.5$ for IC 4182, so

$$M = m - (m - M) = 8.6 - (28.5) = -19.9$$

This absolute magnitude corresponds to a remarkable peak luminosity of 10^{10} $L_{\odot}$.

Review: Whenever astronomers find a Type Ia supernova in a remote galaxy, they can combine this absolute magnitude with the observed maximum apparent magnitude to get the galaxy's distance modulus, from which the galaxy's distance can be easily calculated (just as we did above for the Cepheids in IC 4182). This technique has been used to determine the distances to galaxies hundreds of millions of parsecs away (see Section 25-4).

the astronomer then uses the period-luminosity relation shown in Figure 19-20 to find the Cepheid's average luminosity. Knowing both the apparent brightness and luminosity of the Cepheid, the astronomer can then use the inverse-square law to calculate the distance to the star (see Box 17-2). Box 23-1 presents an examp of this calculation. This procedure is very similar to that use by Harlow Shapley to measure the distances to the Milky Way globular clusters using RR Lyrae variable stars (see Section 22-1

Cepheid variables are intrinsically quite luminous, with average luminosities that can exceed 10^4 $L_\odot$. Hubble realized that for these luminous stars to appear as dim as they were on his photographs of the Andromeda "Nebula," they must be extremely far away. Straightforward calculations using modern data reveal that M31 is some 750 kiloparsecs (2.5 million light-years) from Earth. Based on its angular size, M31 has a diameter of 70 kiloparsecs—larger than the diameter of our own Milky Way Galaxy!

These results prove that the Andromeda "Nebula" is actually an enormous stellar system, far beyond the confines of the Milky Way. Today, this system is properly called the Andromeda Galaxy. (Under good observing conditions, you can actually see this galaxy's central bulge with the naked eye. If you could see the entire Andromeda Galaxy, it would cover an area of the sky roughly 5 times as large as the full moon.) Galaxies are so far away that their distances from us are usually given in millions of parsecs, or *megaparsecs* (Mpc): 1 Mpc = 10^6 pc. For example, the distance to the galaxies in the image that opens this chapter is 17 Mpc.

Hubble's results, which were presented at a meeting of the American Astronomical Society on December 30, 1924, settled the Shapley-Curtis "debate" once and for all. The universe was recognized to be far larger and populated with far bigger objects than anyone had seriously imagined. Hubble had discovered the realm of the galaxies.

CAUTION! In everyday language, many people use the words "galaxy" and "universe" interchangeably. It is true that before Hubble's discoveries our Milky Way Galaxy was thought to constitute essentially the entire universe. But we now know that the universe contains literally billions of galaxies. A single galaxy, vast though it may be, is just a tiny part of the entire observable universe.

CONCEPTCHECK 23-2

If a nearby galaxy were discovered, why would astronomers immediately look for Cepheids?

Answer appears at the end of the chapter.

23-3 Galaxies are classified according to their appearance

Millions of galaxies are visible across every unobscured part of the sky. Although all galaxies are made up of large numbers of stars, they come in a variety of shapes and sizes.

Hubble classified galaxies into four broad categories based on their appearance. These categories form the basis for the **Hubble classification**, a scheme that is still used today. The four classes of galaxies are the spirals, classified S; barred spirals, or SB; ellipticals, E; and irregulars, Irr. Table 23-1 summarizes some key properties of each class. These various types of galaxies differ not only in their shapes but also in the kinds of processes taking place within them.

Spiral Galaxies: Stellar Birthplaces

M51 (Figure 23-2), M31 (Figure 23-3), and M100 (Figure 23-4) are examples of **spiral galaxies**. Figure 23-5 shows that spiral galaxies are characterized by arched lanes of stars, just as is our own Milky Way Galaxy (see Section 22-3). The spiral arms contain young, hot, blue stars and their associated H II regions, indicating ongoing star formation.

Thermonuclear reactions within stars create *metals*, that is, elements heavier than hydrogen or helium (see Section 17-5). These metals are dispersed into space as the stars evolve and die. So, if new stars are being formed from the interstellar matter in spiral galaxies, they will incorporate these metals and be Population I stars (see Section 19-5 and Section 22-2). Indeed, the visible-light spectrum of the disk of a spiral galaxy has strong metal absorption lines. Such a spectrum is a composite of the spectra of many stars and shows tha the stars in the disk are principally of Population I. By contrast, there is relatively little star formation in the central bulges of spiral galaxies, and these regions are dominated by old Population II stars tha have a low metal content. The lack of star formation also explain why the central bulges of spiral galaxies have a yellowish or reddis color; as a population of stars ages, the massive, luminous blue star die off first, leaving only the longer-lived, low-mass red stars.

TABLE 23-1 Some Properties of Galaxies

	Spiral (S) and barred spiral (SB) galaxies	Elliptical galaxies (E)	Irregular galaxies (Irr)
Mass ($M_\odot$)	10^9 to 4×10^{11}	10^5 to 10^{13}	10^8 to 3×10^{10}
Luminosity ($L_\odot$)	10^8 to 2×10^{10}	3×10^5 to 10^{11}	10^7 to 10^9
Diameter (kpc)	5 to 250	1 to 200	1 to 10
Stellar populations	Spiral arms: young Population I Nucleus and throughout disk: Population II and old Population I	Population II and old Population I	mostly Population I
Percentage of observed galaxies	77%	20%*	3%

*This percentage does not include dwarf elliptical galaxies that are as yet too dim and distant to detect. Hence, the actual percentage of galaxies that are ellipticals may be higher than shown here.

(a) Sa (NGC 1357)

(b) Sb (M81)

(c) Sc (NGC 4321)

FIGURE 23-5 R I V U X G

Spiral Galaxies Edwin Hubble classified spiral galaxies according to the texture of their spiral arms and the relative size of their central bulges. Sa galaxies have smooth, broad spiral arms and the largest central bulges, while Sc galaxies have narrow, well-defined arms and the smallest central bulges. (a: Adam Block/Steve Mandel/Jim Rada and Students/NOAO/AURA/NSF; b: Robert Gendler/Science Source; c: FORS Team, 8.2-meter VLT, ESO)

Hubble further classified spiral galaxies according to the texture of the spiral arms and the relative size of the central bulge. Spirals with smooth, broad spiral arms and a fat central bulge are called Sa galaxies, for spiral type *a* (Figure 23-5a); those galaxies with moderately well-defined spiral arms and a moderate-sized central bulge, like M31 and M51, are Sb galaxies (Figure 23-5b); and galaxies with narrow, well-defined spiral arms and a tiny central bulge are Sc galaxies (Figure 23-5c).

The differences between Sa, Sb, and Sc galaxies may be related to the relative amounts of gas and dust they contain. Observations with infrared telescopes (which detect the emission from interstellar dust) and radio telescopes (which detect radiation from interstellar gases such as hydrogen and carbon monoxide) show that about 4% of the mass of a Sa galaxy is in the form of gas and dust. This percentage is 8% for Sb galaxies and 25% for Sc galaxies.

Interstellar gas and dust is the material from which new stars are formed, so an Sc galaxy has a greater proportion of its mass involved in star formation than an Sb or Sa galaxy. Hence, a Sc galaxy has a large disk (where star formation occurs) and a small central bulge (where there is little or no star formation). By comparison, a Sa galaxy, which has relatively little gas and dust, and thus less material from which to form stars, has a large central bulge and only a small star-forming disk.

The central bulge contains more than just stars: It is also thought to contain a supermassive black hole at its center. The mass of the black hole is about 1/1000 the mass of the central bulge, which corresponds to black hole masses of millions to hundreds of millions of solar masses. (The mass of the black hole at the center of our Milky Way is just over 4 million solar masses.) Chapter 24 discusses how these black holes are the "central engines" of quasars and active galaxies.

(a) SBa (NGC 1291)

(b) SBb (M83)

(c) SBc (NGC 1365)

FIGURE 23-6 R I V U X G

Barred Spiral Galaxies As with spiral galaxies, Hubble classified barred spirals according to the texture of their spiral arms (which correlates to the sizes of their central bulges). SBa galaxies have the smoothest spiral arms and the largest central bulges, while SBc galaxies have narrow, well-defined arms and the smallest central bulges. (a: NASA/JPL-Caltech/CTIO; b, c: FORS Team, 8.2-meter VLT, ESO)

CONCEPTCHECK 23-3

When making a sketch of a spiral galaxy with considerable star formation, which areas would you label with *more* star formation? Which areas would have *less*?

Answer appears at the end of the chapter.

Barred Spiral Galaxies: Spirals with an Extra Twist

In **barred spiral galaxies,** such as those shown in Figure 23-6, the spiral arms originate at the ends of a bar-shaped region running through the galaxy's nucleus rather than from the nucleus itself. As with ordinary spirals, Hubble subdivided barred spirals according to the relative size of their central bulge and the character of their spiral arms. A SBa galaxy has a large central bulge and thin, tightly wound spiral arms (Figure 23-6a). Likewise, a SBb galaxy is a barred spiral with a moderate central bulge and moderately wound spiral arms (Figure 23-6b), while a SBc galaxy has lumpy, loosely wound spiral arms and a tiny central bulge (Figure 23-6c). As for ordinary spiral galaxies, the difference between SBa, SBb, and SBc galaxies may be related to the amount of gas and dust in the galaxy.

Bars appear to form naturally in many spiral galaxies. This conclusion comes from computer simulations of galaxies, which set hundreds of thousands of simulated "stars" into orbit around a common center. As the "stars" orbit and exert gravitational forces on one another, a bar structure forms in most cases. Indeed, barred spiral galaxies outnumber ordinary spirals by about two to one. (As we saw in Section 22-2, there is evidence that the Milky Way Galaxy is a barred spiral.)

Why don't all spiral galaxies have bars? According to calculations by Jeremiah Ostriker and P. J. E. Peebles of Princeton University, a bar will not develop if a galaxy is surrounded by a sufficiently massive halo of nonluminous *dark matter.* (In Section 22-4 we saw evidence that our Milky Way Galaxy is surrounded by such a dark matter halo.) The difference between barred spirals and ordinary spirals may thus lie in the amount of dark matter the galaxy possesses. In Section 23-8 we will see compelling evidence for the existence of dark matter in spiral galaxies.

CONCEPTCHECK 23-4

How are galaxies with loosely wrapped arms categorized using Hubble's scheme?

Answer appears at the end of the chapter.

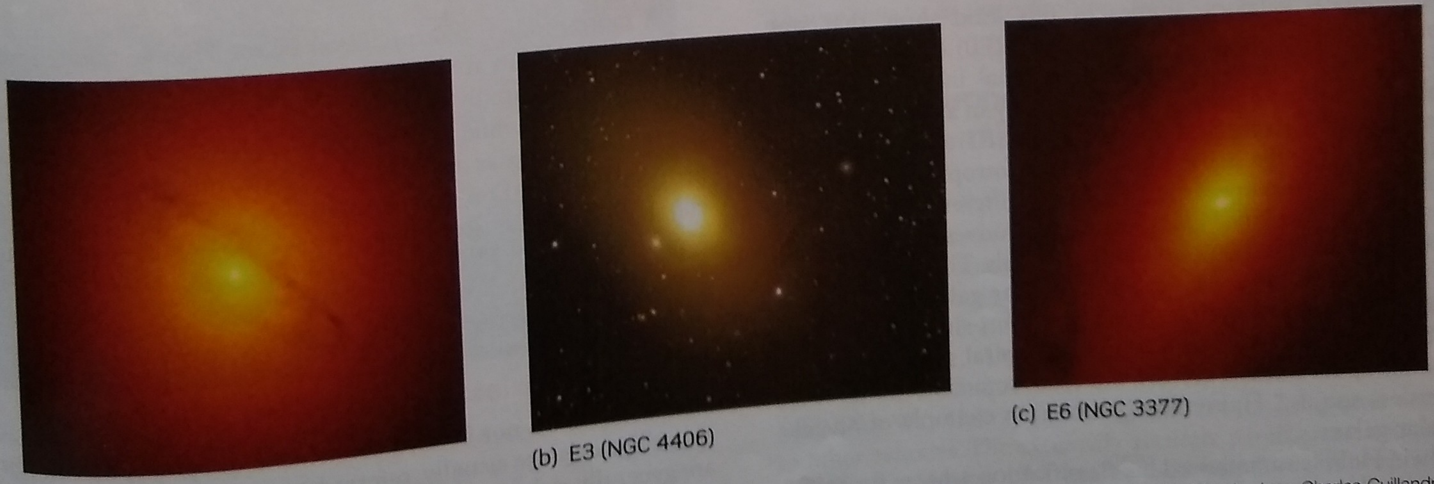
Elliptical Galaxies: From Giants to Dwarfs

Elliptical galaxies, so named because of their distinctly elliptical shapes, have no spiral arms. Hubble subdivided these galaxies according to how round or flattened they look. The roundest elliptical galaxies are called E0 galaxies and the flattest, E7 galaxies. Elliptical galaxies with intermediate amounts of flattening are given designations between these extremes (Figure 23-7).

> **CAUTION!** Unlike the designations for spirals and barred spirals, the classifications E0 through E7 may not reflect the true shape of elliptical galaxies. An E1 or E2 galaxy might actually be a very flattened disk of stars that we just happen to view face-on, and a cigar-shaped E7 galaxy might look spherical if seen end-on. The Hubble scheme classifies galaxies entirely by how they *appear* to us on Earth.

Elliptical galaxies look far less dramatic than their spiral and barred spiral cousins. The reason, as shown by radio and infrared observations, is that ellipticals are virtually devoid of interstellar gas and dust. Consequently, there is little material from which stars could have recently formed, and indeed there is no evidence of young stars in most elliptical galaxies. For the most part, star formation in elliptical galaxies ended long ago. Hence, these galaxies are composed of old, red, Population II stars with only small amounts of metals.

Elliptical galaxies come in a wide range of sizes and masses. Both the largest and the smallest galaxies in the known universe are elliptical. Figure 23-8 shows two **giant elliptical galaxies** that are about 20 times larger than an average galaxy. These giant ellipticals are located near the middle of a large cluster of galaxies in the constellation Virgo. (We will discuss this and other clusters of galaxies in Section 23-6.)



(a) E0 (M105)

(b) E3 (NGC 4406)

(c) E6 (NGC 3377)

FIGURE 23-7 R I **V** U X G
Elliptical Galaxies Hubble classified elliptical galaxies according to how round or flattened they look. A galaxy that appears round is labeled E0, and the flattest-appearing elliptical galaxies are designated E7. (a: Karl Gebhardt (University of Michigan), Tod Lauer (NOAO), and NASA; b: Jean-Charles Cuillandre, Hawaiian Starlight, CFHT; c: Karl Gebhardt (University of Michigan), Tod Lauer (NOAO), and NASA)

FIGURE 23-8 R I V U X G

Giant Elliptical Galaxies The Virgo cluster is a rich, sprawling collection of more than 2000 galaxies about 17 Mpc (56 million ly) from Earth. Only the center of this huge cluster appears in this photograph. The two largest members of this cluster are the giant elliptical galaxies M84 and M86. These galaxies have angular sizes of 5 to 7 arcmin. (Jean-Charles Cuillandre, Hawaiian Starlight, CFHT)

Giant ellipticals are rather rare, but **dwarf elliptical galaxies** are quite common. Dwarf ellipticals are only a fraction the size of their normal counterparts and contain so few stars—only a few million, compared to more than 100 billion (10^{11}) stars in our Milky Way Galaxy—that these galaxies are completely transparent. You can actually see straight through the center of a dwarf galaxy and out the other side, as Figure 23-9 shows.

The visible light from a galaxy is emitted by its stars, so the visible-light spectrum of a galaxy has absorption lines. But because a galaxy's stars are in motion, with some approaching us and others moving away, the Doppler effect smears out and broadens the absorption lines. The average motions of stars in a galaxy can be deduced from the details of this broadening.

For elliptical galaxies, studies of this kind show that star motions are quite random. In a very round (E0) elliptical galaxy, this randomness is **isotropic**, meaning "equal in all directions." Because the stars are whizzing around equally in all directions, the galaxy is genuinely spherical. In a flattened (E7) elliptical galaxy, the randomness of the stellar motions is **anisotropic**, which means that the range of star speeds is different in different directions.

Hubble also identified galaxies that are midway in appearance between ellipticals and the two kinds of spirals. These are denoted as S0 and SB0 galaxies, also called **lenticular galaxies**. Although they look somewhat elliptical, lenticular ("lens-shaped") galaxies have both a central bulge and a disk like spiral galaxies, but no discernible spiral arms. They are therefore sometimes referred to as "armless spirals." Figure 23-10 shows an example of an SB0 lenticular galaxy.

Edwin Hubble summarized his classification scheme for spiral, barred spiral, and elliptical galaxies in a diagram, now called the **tuning fork diagram** for its shape (Figure 23-11).

FIGURE 23-9 R I V U X G

A Dwarf Elliptical Galaxy This diffuse cloud of stars is a nearby E4 dwar elliptical called Leo I. It actually orbits the Milky Way at a distance of about 18 kpc (600,000 ly). Leo I is about 1 kpc (3000 ly) in diameter but contains so few stars that you can see through the galaxy's center. (NASA and The Hubble Heritage Team [STScI/AURA])

CAUTION! When Hubble first drew his tuning fork diagram, he had the idea that it represented an evolutionary sequence. He thought that galaxies evolved over time from the left to the right of the diagram, beginning as ellipticals and eventually becoming either spiral or barred spiral galaxies. We now understand that this evolution of galaxies is not the case at all! For one thing, elliptical galaxies have little or no overall rotation, while spiral and barred spiral galaxies have a substantial amount of overall rotation. There is no way that an elliptical galaxy could suddenly start rotating, which means that it could not evolve into a spiral galaxy.

A more modern interpretation of the Hubble tuning fork diagram is that it is an arrangement of galaxies according to their overall rotation. A rapidly rotating collection of matter in space tends to form a disk, while a slowly rotating collection does not. Thus, the elliptical galaxies at the far left of the tuning fork diagram have little internal rotation and hence no disk. Sa and SBa galaxies have enough overall rotation to form a disk, though their central bulges are still dominant. The galaxies with the greatest amount of overall rotation are Sc and SBc galaxies, in which the central bulges are small and most of the gas, dust, and stars are in the disk.

Irregular Galaxies: Deformed and Dynamic

Galaxies that do not fit into the scheme of spirals, barred spirals, and ellipticals are usually referred to as **irregular galaxies**. They are generally rich in interstellar gas and dust, and have both young and old stars. For lack of any better scheme, the irregular galaxies are sometimes placed between the ends of the tines of the Hubble tuning fork diagram, as in Figure 23-11.

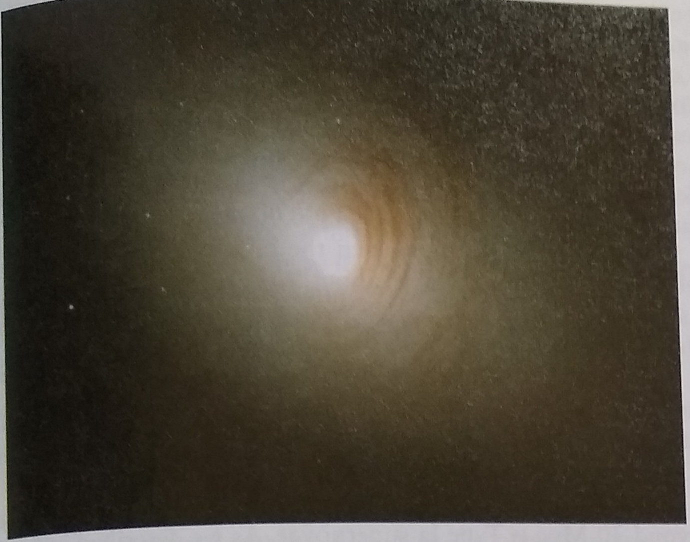


FIGURE 23-10 R I **V** U X G
A Lenticular Galaxy NGC 2787 is classified as a lenticular galaxy because it has a disk but no discernible spiral arms. Its nucleus displays a faint bar (not apparent in this image), so NGC 2787 is denoted as an SB0 galaxy. It lies about 7.4 Mpc (24 million ly) from Earth in the constellation Ursa Major. (NASA and The Hubble Heritage Team, STScI/AURA)

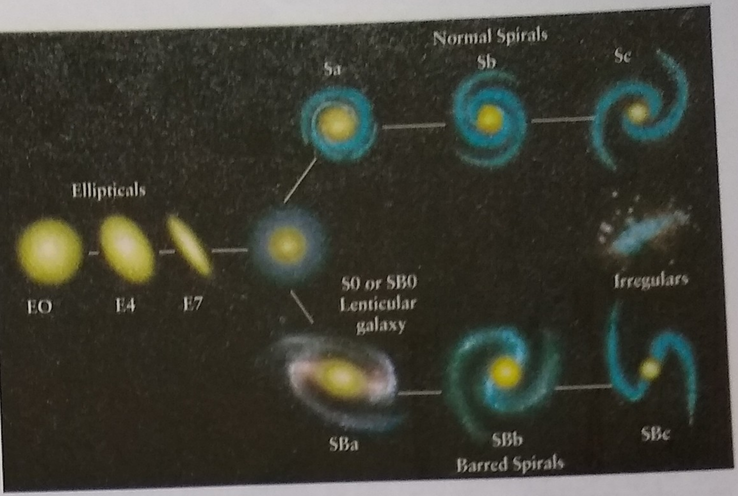


FIGURE 23-11
Hubble's Tuning Fork Diagram Edwin Hubble's classification of regular galaxies is shown in his tuning fork diagram. An elliptical galaxy is classified by how flattened it appears. A spiral or barred spiral galaxy is classified by the texture of its spiral arms and the size of its central bulge. A lenticular galaxy is intermediate between ellipticals and spirals. Irregular galaxies do not fit into this simple classification scheme. The ordering of galaxies does not represent an evolutionary sequence.

Hubble defined two types of irregulars. Irr I galaxies have only hints of organized structure, and have many OB associations and H II regions. The best-known examples of Irr I galaxies are the Large Magellanic Cloud (Figure 23-12) and the Small Magellanic Cloud. Both are nearby companions of our Milky Way and can be seen with the naked eye from southern latitudes. Both these galaxies contain substantial amounts of interstellar gas. Tidal forces exerted on these irregular galaxies by the Milky Way hel to compress the gas, which is why both of the Magellanic cloud are sites of active star formation.

FIGURE 23-12 R I **V** U X G
The Large Magellanic Cloud (LMC) At a distance of only 55 kpc (179,000 ly), this Irr I galaxy is the third closest known companion of our Milky Way Galaxy. About 19 kpc (62,000 ly) across, the LMC spans 22° across the sky, or about 50 times the size of the full moon. One sign that star formation is ongoing in the LMC is the Tarantula Nebula, whose diameter of 250 pc (800 ly) and mass of 5 × 106 M make it the largest known H II region. (NOAO/AURA/NSF)

The other type of irregulars, called Irr II galaxies, have asym metrical, distorted shapes that seem to have been caused by coll sions with other galaxies or by violent activity in their nuclei. M8 shown in Figure 21-16 and in the image that opens Chapter 6, is example of an Irr II galaxy.

CONCEPTCHECK 23-5

Which type of galaxy has almost no ongoing active star formation?

Answer appears at the end of the chapter.

23-4 Astronomers use various techniques to determine the distances to remote galaxies

A key question that astronomers ask about galaxies is "How far away are they?" Knowing the distances to galaxies is essential for learning the structure and history of the universe. Unfortunately, many of the techniques that are used to measure distances w our Milky Way Galaxy cannot be used for the far greater dist to other galaxies. The extremely accurate parallax method th described in Section 17-1 can be used only for stars within 500 pc. Beyond that distance, parallax angles become too sm measure. Spectroscopic parallax, in which the distance to a s

The various methods of distance determination are interrelated because one is used to calibrate another

star cluster is found with the help of the H-R diagram (see Section 17-8), is accurate only out to roughly 10 kpc from Earth; more distant stars or clusters are too dim to give reliable results.

Standard Candles: Variable Stars and Type Ia Supernovae

To determine the distance to a remote galaxy, astronomers look instead for a **standard candle**—an object, such as a star, that lies within that galaxy and for which we know the luminosity (or, equivalently, the absolute magnitude, described in Section 17-3). By measuring how bright the standard candle appears, astronomers can calculate its distance—and hence the distance to the galaxy of which it is part—using the inverse-square law.

The challenge is to find standard candles that are luminous enough to be seen across the tremendous distances to galaxies. To be useful, standard candles should have four properties:

1. They should be luminous so that we can see them out to great distances.
2. We should be fairly certain about their luminosities so that we can be equally certain of any distance calculated from a standard candle's apparent brightness and luminosity.
3. They should be easily identifiable—for example, by the shape of the light curve of a variable star.
4. They should be relatively common so that astronomers can use them to determine the distances to many different galaxies.

For nearby galaxies, Cepheid variable stars make reliable standard candles. These variables can be seen out to about 30 Mpc (100 million ly) using the Hubble Space Telescope, and their luminosity can be determined from their period through the period-luminosity relation depicted in Figure 19-20. Box 23-1 gives an example of using Cepheid variables to determine distances. RR Lyrae stars, which are Population II variable stars often found in globular clusters, can be used as standard candles in a similar way. (We saw in Section 22-1 how RR Lyrae variables helped determine the size of our Galaxy.) Because they are less luminous than Cepheids, RR Lyrae variables can be seen only out to 100 kpc (300,000 ly).

Beyond about 30 Mpc even the brightest Cepheid variables, which have luminosities of about $2 \times 10^4\ L_\odot$, fade from view. Astronomers have tried to use even more luminous stars such as blue supergiants to serve as standard candles. However, this idea is based on the assumption that there is a fixed upper limit on the luminosities of stars, which may not be the case. Hence, these standard candles are not very "standard," and distances measured in this way are somewhat uncertain.

One class of standard candles that astronomers have used beyond 30 Mpc is Type Ia supernovae. As we described in Section 20-9, these supernovae occur when a white dwarf in a close binary system accretes enough matter from its companion to blow itself apart in a thermonuclear conflagration. A Type Ia supernova can reach a maximum luminosity of about $3 \times 10^9\ L_\odot$ (Figure 23-13). If a Type Ia supernova is seen in a distant galaxy and its maximum apparent brightness measured, the inverse-square law can be used to find the galaxy's distance (see Box 23-1).

One complication is that not all Type Ia supernovae are equally luminous. Fortunately, there is a simple relationship between the peak luminosity of a Type Ia supernova and the rate at which the luminosity decreases after the peak: The more slowly the brightness decreases, the more luminous the supernova. Using this relationship, astronomers have measured distances to supernovae more than 1000 Mpc (3 billion ly) from Earth.

(a) M100 in March 2002

(b) M100 in February 2006, showing Supernova 2006X

FIGURE 23-13

A Supernova in a Spiral Galaxy These images from the Very Large Telescope show the spiral galaxy M100 **(a)** before and **(b)** after a Type Ia supernova exploded within the galaxy in 2006. (The two images were made with different color filters, which gives them different appearances.) Such luminous supernovae, which can be seen at extreme distances, are important standard candles used to determine the distances to faraway galaxies. The distance to M100 is also known from observations of Cepheid variables (see Figure 23-4), so this particular supernova can help calibrate Type Ia supernovae as distance indicators. (European Southern Observatory)

Unfortunately, this technique can be used only for galaxies in which we happen to observe a Type Ia supernova. But telescopic surveys now identify many dozens of these supernovae every year, so the number of galaxies whose distances can be measured in this way is continually increasing.

CONCEPTCHECK 23-6

Imagine that a thin cloud of intergalactic dust reduced the observed brightness of a Type Ia supernova found in a distant galaxy. Would astronomers who did not know the dust was there mistakenly assume that the galaxy is farther or closer than it actually is?

Answer appears at the end of the chapter.

Distance Determination without Standard Candles

Other methods for determining the distances to galaxies do not make use of standard candles. One was discovered in the 1970s by the astronomers Brent Tully and Richard Fisher. They found that the width of the hydrogen 21-cm emission line of a spiral galaxy (see Section 22-3) is related to the galaxy's luminosity. This correlation is the **Tully-Fisher relation**—the broader the line, the more luminous the galaxy.

Such a relationship exists because radiation from the approaching side of a rotating galaxy is blueshifted while that from the galaxy's receding side is redshifted. Thus, the 21-cm line is Doppler broadened by an amount directly related to how fast a galaxy is rotating. Rotation speed is related to the galaxy's mass by Newton's form of Kepler's third law. The more massive a galaxy, the more stars it contains and thus the more luminous it is. Consequently, the width of a galaxy's 21-cm line is directly related to its luminosity.

Because line widths can be measured quite accurately, astronomers can use the Tully-Fisher relation to determine the luminosity of a distant spiral galaxy. By combining this information with measurements of apparent brightness, they can calculate the distance to the galaxy. This technique can be used to measure distances of 100 Mpc or more.

Elliptical galaxies do not rotate, so the Tully-Fisher relation cannot be used to determine their distances. But in 1987 the American astronomers Marc Davis and George Djorgovski pointed out a correlation between the size of an elliptical galaxy, the average motions of its stars, and how the galaxy's brightness appears distributed over its surface.

In geometry, three points define a plane, so the relationship among size, motion, and brightness is called the **fundamental plane.** By measuring the last two quantities, an astronomer can use the fundamental plane relationship to determine a galaxy's actual size. And by comparing this to the galaxy's apparent size, the astronomer can calculate the distance to the galaxy using the small-angle formula (see Box 1-1). Ellipticals can be substantially larger and more luminous than spirals, so the fundamental plane can be used at somewhat greater distances than can the Tully-Fisher relation.

CONCEPTCHECK 23-7

Is a galaxy that appears to be quite bright, yet has a narrow width for its emitted hydrogen light, relatively close or very distant from our own Galaxy?

Answer appears at the end of the chapter.

The Distance Ladder

Figure 23-14 shows the ranges of applicability of several important means of determining astronomical distances. Because these ranges overlap, one technique can be used to calibrate another. As an example, astronomers have studied Cepheids in nearby galaxies that have also been host to Type Ia supernovae. The Cepheids provide the distances to these nearby galaxies, making it possible to determine the peak luminosity of each supernova using its maximum apparent brightness and the inverse-square law. Once the peak luminosity is known, it can be used to determine the

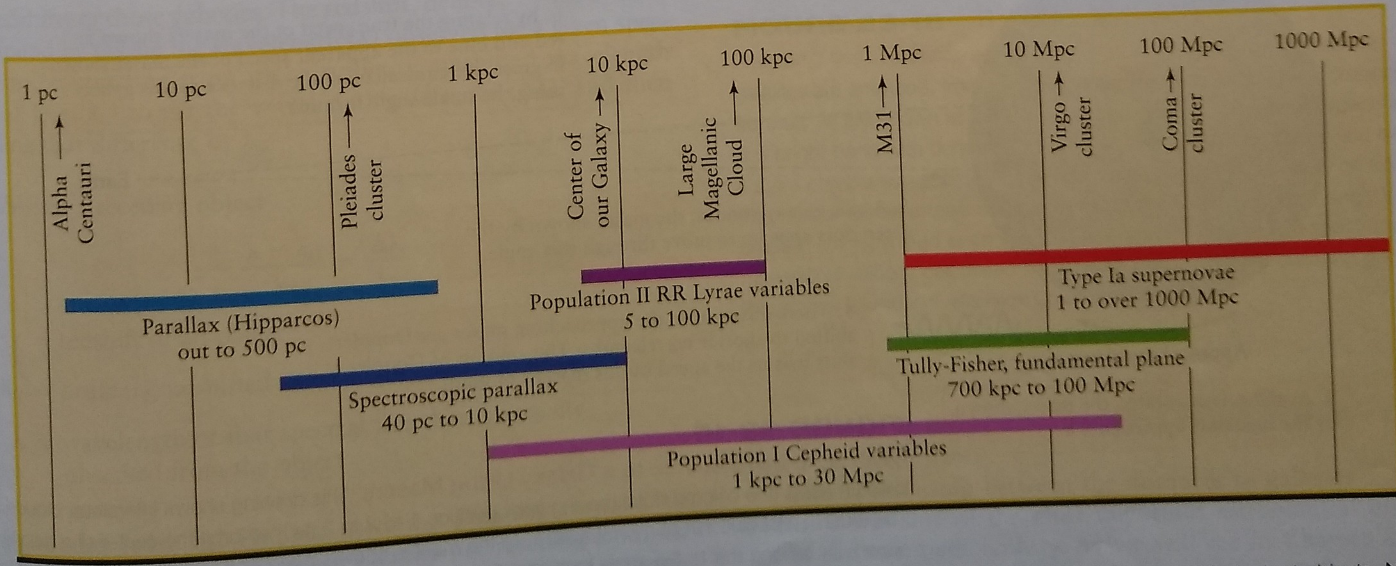


FIGURE 23-14

The Distance Ladder Astronomers employ a variety of techniques for determining the distances to objects beyond the solar system. Because their ranges of applicability overlap, one technique can be used to calibrate another. The arrows indicate distances to several important objects. Note that each division on the scale indicates a tenfold increase in distance, such as from 1 to 10 Mpc.

distance to Type Ia supernovae in more distant galaxies. Because one measuring technique leads us to the next one like rungs on a ladder, the techniques shown in Figure 23-14 (along with others) are referred to collectively as the **distance ladder**.

ANALOGY If you give a slight shake to the bottom of a tall ladder, the top can wobble back and forth alarmingly. A change in distance-measuring techniques used for nearby objects can also have substantial effects on the distances to remote galaxies. For instance, if astronomers discovered that the distances to nearby Cepheids were in error, distance measurements using any technique that is calibrated by Cepheids would be affected as well. (As an example, the distance to the galaxy M100 shown in Figure 23-4 is determined using Cepheids. A Type Ia supernova has been seen in M100, as Figure 23-13 shows, and its luminosity is determined using the Cepheid-derived distance to M100. Any change in the calculated distance to M100 would change the calculated luminosity of the Type Ia supernova, and so it would have an effect on all distances derived from observations of how bright these supernovae appear in other galaxies.) For this reason, astronomers go to great lengths to check the accuracy and reliability of their standard candles.

One distance-measuring technique that has broken free of the distance ladder uses observations of molecular clouds called **masers**. ("Maser" is an acronym for "microwave amplification by stimulated emission of radiation.") Just as an electric current stimulates a laser to emit an intense beam of visible light, nearby luminous stars can stimulate water molecules in a maser to emit intensely at microwave wavelengths. This radiation is so intense that masers can be detected millions of parsecs away.

During the 1990s, Jim Herrnstein and his collaborators used the Very Long Baseline Array (see Section 6-6) to observe a number of masers orbiting in a disk around the center of the spiral galaxy M106. They determined the orbital speed of the masers from the Doppler shift of masers near the edges of the disk, where they are moving most directly toward or away from Earth. They also measured the apparent change in position of masers moving across the face of M106. By relating this apparent speed to the true speed determined from the Doppler shift, they calculated that the masers and the galaxy of which they are part are 7.2 Mpc (23 million ly) from Earth (Figure 23-15).

The maser technique is still in its infancy. But because this technique is independent of all other distance-measuring methods, it is likely to play an important role in calibrating the rungs of the distance ladder.

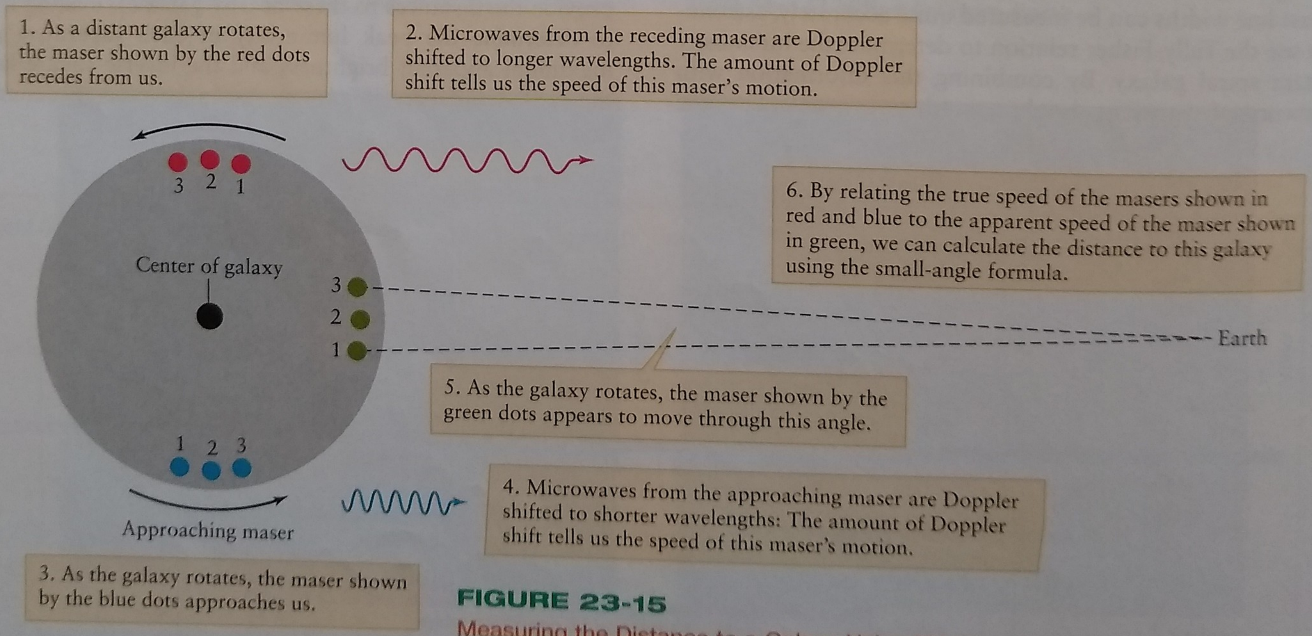
CONCEPTCHECK 23-8

Which of the rungs on the distance ladder depends on an accurate measurement of parallax?

Answer appears at the end of the chapter.

23-5 The Hubble law relates the redshifts of remote galaxies to their distances from Earth

Whenever an astronomer finds an object in the sky that can be seen or photographed, the natural inclination is to attach a



1. As a distant galaxy rotates, the maser shown by the red dots recedes from us.

2. Microwaves from the receding maser are Doppler shifted to longer wavelengths. The amount of Doppler shift tells us the speed of this maser's motion.

3. As the galaxy rotates, the maser shown by the blue dots approaches us.

4. Microwaves from the approaching maser are Doppler shifted to shorter wavelengths: The amount of Doppler shift tells us the speed of this maser's motion.

5. As the galaxy rotates, the maser shown by the green dots appears to move through this angle.

6. By relating the true speed of the masers shown in red and blue to the apparent speed of the maser shown in green, we can calculate the distance to this galaxy using the small-angle formula.

FIGURE 23-15

Measuring the Distance to a Galaxy Using Masers This drawing shows interstellar clouds called masers (the colored dots) moving from position 1 to 2 to 3 as they orbit the center of a galaxy. The redshift and blueshift of microwaves from the masers shown in red and blue tell us their orbital speed. By relating this to the angle through which the masers shown in green appear to move in a certain amount of time, we can calculate the distance to the galaxy.

spectrograph to a telescope and record the spectrum. As long ago as 1914, Vesto M. Slipher, working at the Lowell Observatory in Arizona, began taking spectra of "spiral nebulae"—a name used before they were known to be galaxies. He was surprised to discover that of the 15 spiral nebulae he studied, the spectral lines of 11 were shifted toward the red end of the spectrum, indicating that they were moving away from Earth.

This marked dominance of redshifts over blueshifts was presented by Curtis in the 1920 Shapley-Curtis "debate" as evidence that these spiral nebulae could not be ordinary nebulae in our Milky Way Galaxy. It was only later that astronomers realized that the redshifts of spiral nebulae—that is, galaxies—reveal a basic law of our expanding universe.

Redshift, Distance, and the Hubble Law

> The greater the redshift of a distant galaxy, the farther away it is

During the 1920s, Edwin Hubble and Milton Humason photographed the spectra of many galaxies with the 100-inch (2.5-meter) telescope on Mount Wilson in California. By observing the apparent brightnesses and pulsation periods of Cepheid variables in these galaxies, they were also able to measure the distance to each galaxy (see Section 23-2). Hubble and Humason found that most galaxies show a redshift in their spectrum. They also found a direct correlation between the distance to a galaxy and its redshift:

The more distant a galaxy, the greater its redshift and the more rapidly it is receding from us.

In other words, nearby galaxies are moving away from us slowly, and more distant galaxies are rushing away from us much more rapidly. Figure 23-16 shows this relationship for five representative elliptical galaxies. This universal recessional movement is referred to as the **Hubble flow.**

Hubble estimated the distances to a number of galaxies and the redshifts of those galaxies. The **redshift,** denoted by the symbol z, is found by taking the wavelength (λ) observed for a given spectral line, subtracting from it the ordinary, unshifted wavelength of that line (λ_0) to get the wavelength difference ($\Delta\lambda$), and then dividing that difference by λ_0:

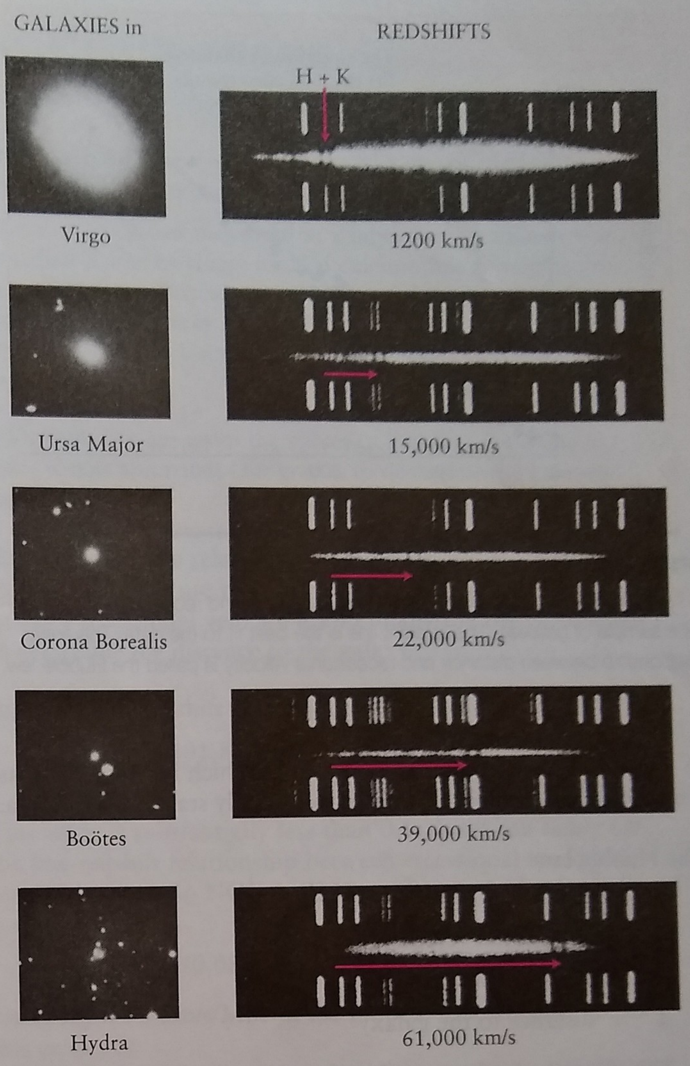
Redshift of a receding object

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

z = redshift of an object

λ_0 = ordinary, unshifted wavelength of a spectral line

λ = wavelength of that spectral line that is actually observed from the object



The more distant the galaxy...

...the greater its redshift and the more rapidly it is receding from us.

FIGURE 23-16 R I V U X G **Relating the Distances and Redshifts of Galaxies** These five galaxies are arranged, from top to bottom, in order of increasing distance from us. All are shown at the same magnification. Each galaxy's spectrum is a bright band with dark absorption lines; the bright lines above and below it are a comparison spectrum of a light source at the observatory on Earth. The horizontal red arrows show how much the H and K lines of singly ionized calcium are redshifted in each galaxy's spectrum. Below each spectrum is the recessional velocity calculated from the redshift. The more distant a galaxy is, the greater its redshift. (Carnegie Observatories)

From the redshifts, Hubble used the Doppler formula to calculate the speed at which these galaxies are receding from us. Box 23-2 describes this calculation. Plotting the data on a graph of distance versus speed, Hubble found that the points lie near a straight line. Figure 23-17 is a modern version of Hubble's graph based on recent data.

This relationship between the distances to galaxies and their redshifts was one of the most important astronomical discoveries of the twentieth century. As we will see in Chapter 26, this relationship tells us that we are living in an expanding universe.

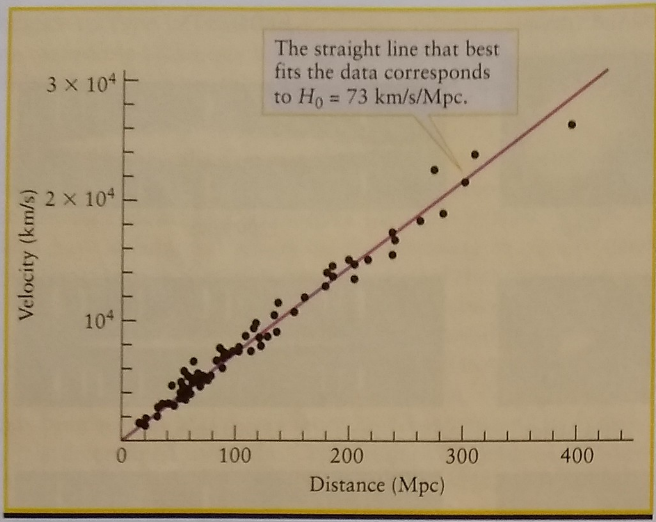


FIGURE 23-17

The Hubble Law This graph plots the distances and recessional velocities of a sample of galaxies. The straight line is the best fit to the data. This linear relationship between distance and recessional velocity is called the Hubble law.

In 1929, Hubble published this discovery, which is now known as the **Hubble law.** The Hubble law is most easily stated as a formula:

The Hubble law

$$v = H_0 d$$

v = recessional velocity of a galaxy
H_0 = Hubble constant
d = distance to the galaxy

This formula is the equation for the straight line displayed in Figure 23-17, and the **Hubble constant** H_0 is the slope of this straight line. From the data plotted on this graph we find that H_0 = 73 km/s/Mpc (say "73 kilometers per second per megaparsec"). In other words, for each million parsecs to a galaxy, the galaxy's speed away from us increases by 73 km/s. For example, a galaxy located 100 million parsecs from Earth should be rushing away from us with a speed of 7300 km/s. (In other books you may see the units of the Hubble constant written with exponents: 73 km s^{-1} Mpc^{-1}.)

CAUTION! A common misconception about the Hubble law is that *all* galaxies are moving away from the Milky Way. The reality is that galaxies have their own neighbor-induced motions relative to one another, due to their mutual gravitational attraction of neighboring galaxies. Astronomers call this neighbor-induced motion *intrinsic velocity.* For nearby galaxies, the speed of the Hubble flow is small compared to these intrinsic velocities. Hence, some of the nearest galaxies, including the Andromeda Galaxy (shown in Figure 23-3), are actually approaching us and have blueshifts rather than redshifts. But for distant galaxies, the Hubble speed $v = H_0 d$ is much greater than any intrinsic motion that the galaxies might have. Even if the intrinsic velocity of such a distant galaxy is toward the Milky Way, the fast-moving Hubble flow sweeps that galaxy away from us.

CONCEPTCHECK 23-9

In Figure 23-17, which follows Hubble's law, consider galaxies at 100 Mpc and 200 Mpc. Which galaxy has the larger redshift?

Answer appears at the end of the chapter.

Pinning Down the Hubble Constant

A precise value of the Hubble constant has been a topic of heated debate among astronomers for several decades. The problem is that while redshifts are relatively easy to measure in a reliable way, distances to galaxies (especially remote galaxies) are not, as we saw in Section 23-4. Hence, astronomers who use different methods of determining galactic distances have obtained different values of H_0. To see why different values are measured, it is helpful to rewrite the Hubble law as

$$H_0 = \frac{v}{d}$$

This equation shows that if galaxies of a given recessional velocity (v) are far away (so d is large), the Hubble constant H_0 must be relatively small. But if these galaxies are relatively close (so d is small), then H_0 must have a larger value.

In the past, astronomers who used Type Ia supernovae for determining galactic distances found galaxies to be farther away than their colleagues who employed the Tully-Fisher relation. Therefore, the supernova adherents found values of H_0 in the range from about 40 to 65 km/s/Mpc, while the values from the Tully-Fisher relation ranged from about 80 to 100 km/s/Mpc.

In the past few years, the Hubble Space Telescope has been used to observe Cepheid variables with unprecedented precision and in galaxies as far away as 30 Mpc (100 million ly). These observations and others suggest a value of the Hubble constant of about 73 km/s/Mpc, with an uncertainty of no more than 10%. At the same time, reanalysis of the supernova and Tully-Fisher results have brought the values of H_0 from these techniques closer to the Hubble Space Telescope Cepheid value. We will adopt the value H_0 = 73 km/s/Mpc in this book.

Determining the value of H_0 has been an important task of astronomers for a very simple reason: The Hubble constant is one of the most important numbers in all astronomy. It expresses the rate at which the universe is expanding and, as we will see in Chapter 25, even helps give the age of the universe. Furthermore, the Hubble law can be used to determine the distances to extremely remote galaxies. If the redshift of a galaxy is known, the Hubble law can be used to determine its distance from Earth. Thus, the value of the Hubble constant helps determine the distances of the most remote objects in the universe that astronomers can observe.

Because the value of H_0 remains somewhat uncertain, astronomers often express the distance to a remote galaxy simply in terms of its redshift z (which can be measured very accurately). Given the redshift, the distance to this galaxy can be calculated from the Hubble law, but the distance obtained in this way will depend on the particular value of H_0 adopted. Rather than going through these calculations, an astronomer might simply say that a certain galaxy is "at $z = 0.128$." From the Hubble law relating redshift and distance, this redshift makes it clear that the galaxy in question is more distant than one at $z = 0.120$ but not as distant as one

BOX 23-2 TOOLS OF THE ASTRONOMER'S TRADE

The Hubble Law, Redshifts, and Recessional Velocities

Suppose that you aim a telescope at a distant galaxy. The galaxy will be moving away from you in the Hubble flow. You take a spectrum of the galaxy and find that the spectral lines are shifted toward the red end of the spectrum. For example, a particular spectral line whose normal wavelength is λ_0 appears in the galaxy's spectrum at a longer wavelength λ. The spectral line has thus been shifted by an amount $\Delta\lambda = \lambda - \lambda_0$. The redshift of the galaxy, z, is given by

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

The redshift means that the galaxy is receding from us. According to the Hubble law, the recessional velocity v of a galaxy is related to its distance d from Earth by

$$v = H_0 d$$

where H_0 is the Hubble constant. We can rewrite this equation

$$d = \frac{v}{H_0}$$

Given the value of H_0, we can find the distance d to the galaxy if we know how to determine the recessional velocity v from the redshift z.

If the redshift is not too great (so that the redshift z is much less than 1), we can use the following Doppler shift equation to find the recessional speed:

$$z = \frac{v}{c} \text{ (valid for low speeds only)}$$

where c is the speed of light. For example, a 5% shift in wavelength ($z = 0.05$) corresponds to a recessional velocity of 5% of the speed of light ($v = 0.05c$).

For larger redshifts (around $z = 1$ or greater), a more complicated equation is needed to determine the recessional velocity. A small redshift can be explained by the Doppler shift as we have used here. However, as we will see in Chapter 25, larger redshifts arise from a large *expansion of space* and cannot be described as a simple Doppler shift. In fact, for galaxies at redshifts greater than about $z > 1.5$, recessional speeds exceed the speed of light. Due to the unique attributes of expanding space, faster-than-light recession is not a violation of Einstein's laws.

EXAMPLE: When measured in a laboratory on Earth, the so-called K line of singly ionized calcium has a wavelength $\lambda_0 = 393.3$ nm. But when you observe the spectrum of the giant elliptical galaxy NGC 4889, you find this spectral line at $\lambda = 401.8$ nm. Using $H_0 = 73$ km/s/Mpc, find the distance to this galaxy.

Situation: We are given the values of λ and λ_0 for a line in this galaxy's spectrum. Our goal is to determine the galaxy's distance d.

Tools: We use the relationship $z = (\lambda - \lambda_0)/\lambda_0$ to determine the redshift. We then use the appropriate formula to determine the galaxy's recessional velocity v, and finally use the Hubble law to determine the distance to the galaxy.

Answer: The redshift of this galaxy is

$$z = \frac{401.8 \text{ nm} - 393.3 \text{ nm}}{393.3 \text{ nm}} = 0.0216$$

This value is substantially less than 0.1, so we can safely use the low-redshift relationship between recessional speed and redshift: $v = zc$. So NGC 4889 is moving away from us with a speed

$$v = zc = (0.0216)(3 \times 10^5 \text{ km/s}) = 6480 \text{ km/s}$$

Using $H_0 = 73$ km/s/Mpc in the Hubble law, the distance to this galaxy is

$$d = \frac{v}{H_0} = \frac{6480 \text{ km/s}}{73 \text{ km/s/Mpc}} = 89 \text{ Mpc}$$

Review: This galaxy is receding from us at 0.0216 (2.16%) of the speed of light, and it is 89 megaparsecs (290 million light-years) away. Thus the light we see from NGC 4889 today left the galaxy 290 million years ago, even before the first dinosaurs appeared on Earth.

at $z = 0.130$. When astronomers use redshift to describe distance, they are making use of the following general rule:

The greater the redshift of a distant galaxy, the greater its distance.

CONCEPTCHECK 23-10

Although nearly all distant galaxies have measureable redshifts, the relatively nearby Andromeda Galaxy exhibits an overall blueshift. What does this mean about the Andromeda Galaxy's movement?

CALCULATIONCHECK 23-1

What is the redshift z-value for a galaxy that has a galaxy spectral line shifted to 725.6 nm when a stationary object would emit the line at 656.3 nm?

CALCULATIONCHECK 23-2

What is the distance to a galaxy that is observed to have a recessional velocity of 10,000 km/s?

Answers appear at the end of the chapter.