



26

GALAXIES

Figure 26.1 Spiral Galaxy. NGC 6946 is a spiral galaxy also known as the “Fireworks galaxy.” It is at a distance of about 18 million light-years, in the direction of the constellations Cepheus and Cygnus. It was discovered by William Herschel in 1798. This galaxy is about one-third the size of the Milky Way. Note on the left how the colors of the galaxy change from the yellowish light of old stars in the center to the blue color of hot, young stars and the reddish glow of hydrogen clouds in the spiral arms. As the image shows, this galaxy is rich in dust and gas, and new stars are still being born here. In the right-hand image, the x-rays coming from this galaxy are shown in purple, which has been added to other colors showing visible light. (Credit left: modification of work by NASA, ESA, STScI, R. Gendler, and the Subaru Telescope (NAOJ)); credit right: modification of work by X-ray: NASA/CXC/MSSL/R.Soria et al, Optical: AURA/Gemini OBs)

Chapter Outline

- 26.1 The Discovery of Galaxies
- 26.2 Types of Galaxies
- 26.3 Properties of Galaxies
- 26.4 The Extragalactic Distance Scale
- 26.5 The Expanding Universe



Thinking Ahead

In the last chapter, we explored our own Galaxy. But is it the only one? If there are others, are they like the Milky Way? How far away are they? Can we see them? As we shall learn, some galaxies turn out to be so far away that it has taken billions of years for their light to reach us. These remote galaxies can tell us what the universe was like when it was young.

In this chapter, we start our exploration of the vast realm of galaxies. Like tourists from a small town making their first visit to the great cities of the world, we will be awed by the beauty and variety of the galaxies. And yet, we will recognize that much of what we see is not so different from our experiences at home, and we will be impressed by how much we can learn by looking at structures built long ago.

We begin our voyage with a guide to the properties of galaxies, much as a tourist begins with a guidebook to the main features of the cities on the itinerary. In later chapters, we will look more carefully at the past history of galaxies, how they have changed over time, and how they acquired their many different forms. First, we'll begin our voyage through the galaxies with the question: is our Galaxy the only one?

26.1 THE DISCOVERY OF GALAXIES

Learning Objectives

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

- › Describe the discoveries that confirmed the existence of galaxies that lie far beyond the Milky Way Galaxy
- › Explain why galaxies used to be called nebulae and why we don't include them in that category any more

Growing up at a time when the Hubble Space Telescope orbits above our heads and giant telescopes are springing up on the great mountaintops of the world, you may be surprised to learn that we were not sure about the existence of other galaxies for a very long time. The very idea that other galaxies exist used to be controversial. Even into the 1920s, many astronomers thought the Milky Way encompassed *all* that exists in the universe. The evidence found in 1924 that meant our Galaxy is not alone was one of the great scientific discoveries of the twentieth century.

It was not that scientists weren't asking questions. They questioned the composition and structure of the universe as early as the eighteenth century. However, with the telescopes available in earlier centuries, galaxies looked like small fuzzy patches of light that were difficult to distinguish from the star clusters and gas-and-dust clouds that are part of our own Galaxy. All objects that were not sharp points of light were given the same name, *nebulae*, the Latin word for "clouds." Because their precise shapes were often hard to make out and no techniques had yet been devised for measuring their distances, the nature of the nebulae was the subject of much debate.

As early as the eighteenth century, the philosopher Immanuel Kant (1724–1804) suggested that some of the nebulae might be distant systems of stars (other Milky Ways), but the evidence to support this suggestion was beyond the capabilities of the telescopes of that time.

Other Galaxies

By the early twentieth century, some nebulae had been correctly identified as star clusters, and others (such as the Orion Nebula) as gaseous nebulae. Most nebulae, however, looked faint and indistinct, even with the best telescopes, and their distances remained unknown. (For more on how such nebulae are named, by the way, see the feature box on [Naming the Nebulae](#) in the chapter on interstellar matter.) If these nebulae were nearby, with distances comparable to those of observable stars, they were most likely clouds of gas or groups of stars within our Galaxy. If, on the other hand, they were remote, far beyond the edge of the Galaxy, they could be other star systems containing billions of stars.

To determine what the nebulae are, astronomers had to find a way of measuring the distances to at least some of them. When the 2.5-meter (100-inch) telescope on Mount Wilson in Southern California went into operation, astronomers finally had the large telescope they needed to settle the controversy.

Working with the 2.5-meter telescope, Edwin Hubble was able to resolve individual stars in several of the brighter spiral-shaped nebulae, including M31, the great spiral in Andromeda ([Figure 26.2](#)). Among these stars, he discovered some faint variable stars that—when he analyzed their light curves—turned out to be cepheids. Here were reliable indicators that Hubble could use to measure the distances to the nebulae using the technique pioneered by Henrietta Leavitt (see the chapter on [Celestial Distances](#)). After painstaking work, he estimated that the Andromeda galaxy was about 900,000 light-years away from us. At that enormous distance, it had to be a separate galaxy of stars located well outside the boundaries of the Milky Way. Today, we know the Andromeda galaxy is actually slightly more than twice as distant as Hubble's first estimate, but his conclusion

about its true nature remains unchanged.



Figure 26.2 Andromeda Galaxy. Also known by its catalog number M31, the Andromeda galaxy is a large spiral galaxy very similar in appearance to, and slightly larger than, our own Galaxy. At a distance of about 2.5 million light-years, Andromeda is the spiral galaxy that is nearest to our own in space. Here, it is seen with two of its satellite galaxies, M32 (top) and M110 (bottom). (credit: Adam Evans)

No one in human history had ever measured a distance so great. When Hubble's paper on the distances to nebulae was read before a meeting of the American Astronomical Society on the first day of 1925, the entire room erupted in a standing ovation. A new era had begun in the study of the universe, and a new scientific field—extragalactic astronomy—had just been born.

VOYAGERS IN ASTRONOMY



Edwin Hubble: Expanding the Universe

The son of a Missouri insurance agent, Edwin Hubble ([Figure 26.3](#)) graduated from high school at age 16. He excelled in sports, winning letters in track and basketball at the University of Chicago, where he studied both science and languages. Both his father and grandfather wanted him to study law, however, and he gave in to family pressure. He received a prestigious Rhodes scholarship to Oxford University in England, where he studied law with only middling enthusiasm. Returning to the United States, he spent a year teaching high school physics and Spanish as well as coaching basketball, while trying to determine his life's direction.



Figure 26.3 Edwin Hubble (1889–1953). Edwin Hubble established some of the most important ideas in the study of galaxies.

The pull of astronomy eventually proved too strong to resist, and so Hubble went back to the University of Chicago for graduate work. Just as he was about to finish his degree and accept an offer to work at the soon-to-be completed 5-meter telescope, the United States entered World War I, and Hubble enlisted as an officer. Although the war had ended by the time he arrived in Europe, he received more officer's training abroad and enjoyed a brief time of further astronomical study at Cambridge before being sent home.

In 1919, at age 30, he joined the staff at Mount Wilson and began working with the world's largest telescope. Ripened by experience, energetic, disciplined, and a skillful observer, Hubble soon established some of the most important ideas in modern astronomy. He showed that other galaxies existed, classified them on the basis of their shapes, found a pattern to their motion (and thus put the notion of an expanding universe on a firm observational footing), and began a lifelong program to study the distribution of galaxies in the universe. Although a few others had glimpsed pieces of the puzzle, it was Hubble who put it all together and showed that an understanding of the large-scale structure of the universe was feasible.

His work brought Hubble much renown and many medals, awards, and honorary degrees. As he became better known (he was the first astronomer to appear on the cover of *Time* magazine), he and his wife enjoyed and cultivated friendships with movie stars and writers in Southern California. Hubble was instrumental (if you'll pardon the pun) in the planning and building of the 5-meter telescope on Palomar Mountain, and he had begun to use it for studying galaxies when he passed away from a stroke in 1953.

When astronomers built a space telescope that would allow them to extend Hubble's work to distances he could only dream about, it seemed natural to name it in his honor. It was fitting that observations with the Hubble Space Telescope (and his foundational work on expansion of the universe) contributed to the 2011 Nobel Prize in Physics, given for the discovery that the expansion of the universe is accelerating (a topic we will expand upon in the chapter on [The Big Bang](#)).

26.2 TYPES OF GALAXIES

Learning Objectives

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

- › Describe the properties and features of elliptical, spiral, and irregular galaxies
- › Explain what may cause a galaxy's appearance to change over time

Having established the existence of other galaxies, Hubble and others began to observe them more closely—noting their shapes, their contents, and as many other properties as they could measure. This was a daunting task in the 1920s when obtaining a single photograph or spectrum of a galaxy could take a full night of tireless observing. Today, larger telescopes and electronic detectors have made this task less difficult, although observing the most distant galaxies (those that show us the universe in its earliest phases) still requires enormous effort.

The first step in trying to understand a new type of object is often simply to describe it. Remember, the first step in understanding stellar spectra was simply to sort them according to appearance (see [Analyzing Starlight](#)). As it turns out, the biggest and most luminous galaxies come in one of two basic shapes: either they are flatter and have spiral arms, like our own Galaxy, or they appear to be elliptical (blimp- or cigar-shaped). Many smaller galaxies, in contrast, have an irregular shape.

Spiral Galaxies

Our own Galaxy and the Andromeda galaxy are typical, large **spiral galaxies** (see [Figure 26.2](#)). They consist of a central bulge, a halo, a disk, and spiral arms. Interstellar material is usually spread throughout the disks of spiral galaxies. Bright emission nebulae and hot, young stars are present, especially in the spiral arms, showing that new star formation is still occurring. The disks are often dusty, which is especially noticeable in those systems that we view almost edge on ([Figure 26.4](#)).

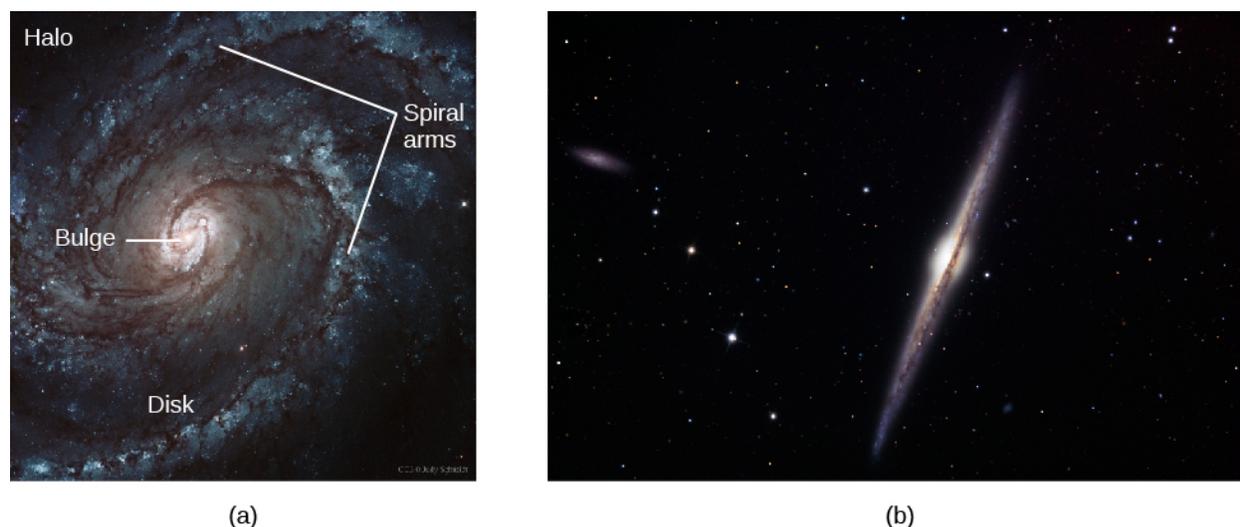


Figure 26.4 Spiral Galaxies. (a) The spiral arms of M100, shown here, are bluer than the rest of the galaxy, indicating young, high-mass stars and star-forming regions. (b) We view this spiral galaxy, NGC 4565, almost exactly edge on, and from this angle, we can see the dust in the plane of the galaxy; it appears dark because it absorbs the light from the stars in the galaxy. (credit a: modification of work by Hubble Legacy Archive, NASA, ESA, and Judy Schmidt; credit b: modification of work by "Jschulman555"/ Wikimedia)

In galaxies that we see face on, the bright stars and emission nebulae make the arms of spirals stand out like

those of a pinwheel on the fourth of July. Open star clusters can be seen in the arms of nearer spirals, and globular clusters are often visible in their halos. Spiral galaxies contain a mixture of young and old stars, just as the Milky Way does. All spirals rotate, and the direction of their spin is such that the arms appear to trail much like the wake of a boat.

About two-thirds of the nearby spiral galaxies have boxy or peanut-shaped bars of stars running through their centers (**Figure 26.5**). Showing great originality, astronomers call these galaxies barred spirals.



Figure 26.5 Barred Spiral Galaxy. NGC 1300, shown here, is a barred spiral galaxy. Note that the spiral arms begin at the ends of the bar. (credit: NASA, ESA, and the Hubble Heritage Team(STScI/AURA))

As we noted in **The Milky Way Galaxy** chapter, our Galaxy has a modest bar too (see **Figure 25.10**). The spiral arms usually begin from the ends of the bar. The fact that bars are so common suggests that they are long lived; it may be that most spiral galaxies form a bar at some point during their evolution.

In both barred and unbarred spiral galaxies, we observe a range of different shapes. At one extreme, the central bulge is large and luminous, the arms are faint and tightly coiled, and bright emission nebulae and supergiant stars are inconspicuous. Hubble, who developed a system of classifying galaxies by shape, gave these galaxies the designation Sa. Galaxies at this extreme may have no clear spiral arm structure, resulting in a lens-like appearance (they are sometimes referred to as lenticular galaxies). These galaxies seem to share as many properties with elliptical galaxies as they do with spiral galaxies

At the other extreme, the central bulge is small and the arms are loosely wound. In these Sc galaxies, luminous stars and emission nebulae are very prominent. Our Galaxy and the Andromeda galaxy are both intermediate between the two extremes. Photographs of spiral galaxies, illustrating the different types, are shown in **Figure 26.6**, along with elliptical galaxies for comparison.

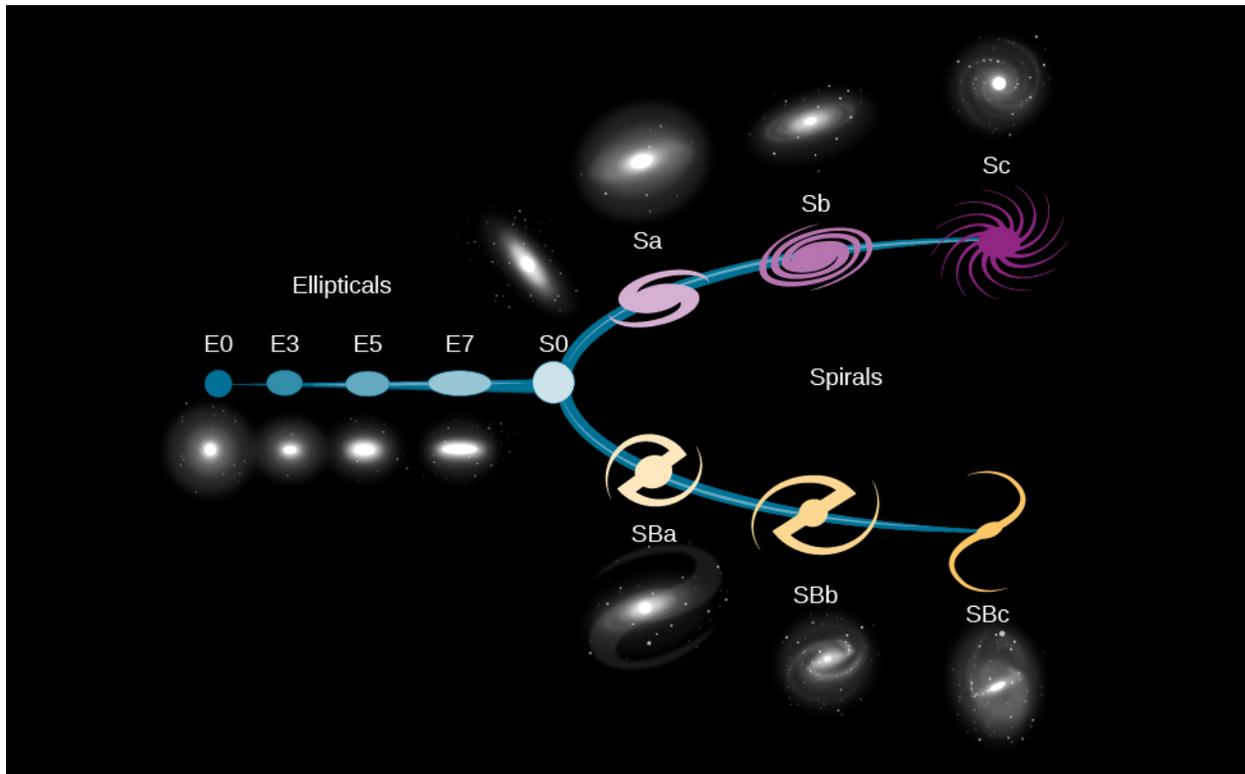


Figure 26.6 Hubble Classification of Galaxies. This figure shows Edwin Hubble's original classification of galaxies. Elliptical galaxies are on the left. On the right, you can see the basic spiral shapes illustrated, alongside images of actual barred and unbarred spirals. (credit: modification of work by NASA, ESA)

The luminous parts of spiral galaxies appear to range in diameter from about 20,000 to more than 100,000 light-years. Recent studies have found that there is probably a large amount of galactic material that extends well beyond the apparent edge of galaxies. This material appears to be thin, cold gas that is difficult to detect in most observations.

From the observational data available, the masses of the visible portions of spiral galaxies are estimated to range from 1 billion to 1 trillion Suns (10^9 to $10^{12} M_{\text{Sun}}$). The total luminosities of most spirals fall in the range of 100 million to 100 billion times the luminosity of our Sun (10^8 to $10^{11} L_{\text{Sun}}$). Our Galaxy and M31 are relatively large and massive, as spirals go. There is also considerable dark matter in and around the galaxies, just as there is in the Milky Way; we deduce its presence from how fast stars in the outer parts of the Galaxy are moving in their orbits.

Elliptical Galaxies

Elliptical galaxies consist almost entirely of old stars and have shapes that are spheres or ellipsoids (somewhat squashed spheres) (Figure 26.7). They contain no trace of spiral arms. Their light is dominated by older reddish stars (the population II stars discussed in [The Milky Way Galaxy](#)). In the larger nearby ellipticals, many globular clusters can be identified. Dust and emission nebulae are not conspicuous in elliptical galaxies, but many do contain a small amount of interstellar matter.

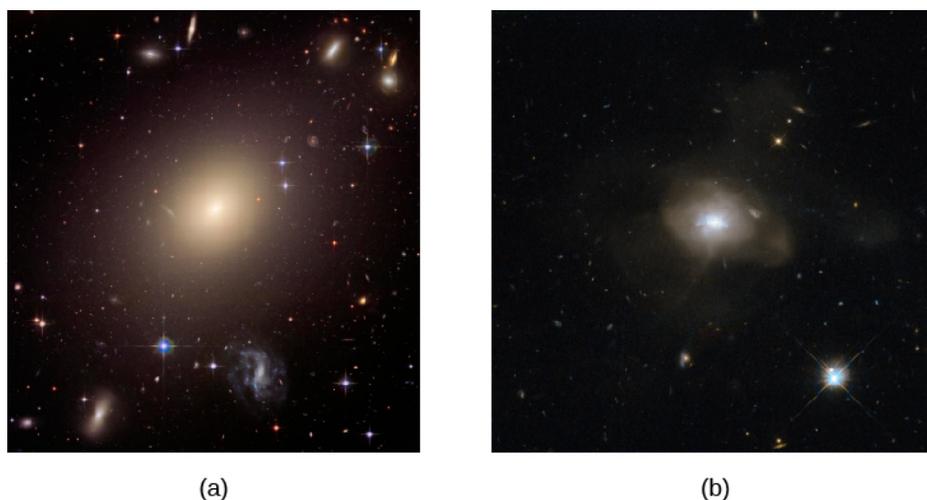


Figure 26.7 Elliptical Galaxies. (a) ESO 325-G004 is a giant elliptical galaxy. Other elliptical galaxies can be seen around the edges of this image. (b) This elliptical galaxy probably originated from the collision of two spiral galaxies. (credit a: modification of work by NASA, ESA, and The Hubble Heritage Team (STScI/AURA); credit b: modification of work by ESA/Hubble, NASA)

Elliptical galaxies show various degrees of flattening, ranging from systems that are approximately spherical to those that approach the flatness of spirals. The rare giant ellipticals (for example, ESO 325-G004 in [Figure 26.7](#)) reach luminosities of $10^{11} L_{\text{Sun}}$. The mass in a giant elliptical can be as large as $10^{13} M_{\text{Sun}}$. The diameters of these large galaxies extend over several hundred thousand light-years and are considerably larger than the largest spirals. Although individual stars orbit the center of an elliptical galaxy, the orbits are not all in the same direction, as occurs in spirals. Therefore, ellipticals don't appear to rotate in a systematic way, making it difficult to estimate how much dark matter they contain.

We find that elliptical galaxies range all the way from the giants, just described, to dwarfs, which may be the most common kind of galaxy. *Dwarf ellipticals* (sometimes called dwarf spheroidals) escaped our notice for a long time because they are very faint and difficult to see. An example of a dwarf elliptical is the Leo I Dwarf Spheroidal galaxy shown in [Figure 26.8](#). The luminosity of this typical dwarf is about equal to that of the brightest globular clusters.

Intermediate between the giant and dwarf elliptical galaxies are systems such as M32 and M110, the two companions of the Andromeda galaxy. While they are often referred to as dwarf ellipticals, these galaxies are significantly larger than galaxies such as Leo I.



Figure 26.8 Dwarf Elliptical Galaxy. M32, a dwarf elliptical galaxy and one of the companions to the giant Andromeda galaxy M31. M32 is a dwarf by galactic standards, as it is only 2400 light-years across. (credit: NOAO/AURA/NSF)

Irregular Galaxies

Hubble classified galaxies that do not have the regular shapes associated with the categories we just described into the catchall bin of an **irregular galaxy**, and we continue to use his term. Typically, irregular galaxies have lower masses and luminosities than spiral galaxies. Irregular galaxies often appear disorganized, and many are undergoing relatively intense star formation activity. They contain both young population I stars and old population II stars.

The two best-known irregular galaxies are the Large Magellanic Cloud and Small Magellanic Cloud ([Figure 26.9](#)), which are at a distance of a little more than 160,000 light-years away and are among our nearest extragalactic neighbors. Their names reflect the fact that Ferdinand Magellan and his crew, making their round-the-world journey, were the first European travelers to notice them. Although not visible from the United States and Europe, these two systems are prominent from the Southern Hemisphere, where they look like wispy clouds in the night sky. Since they are only about one-tenth as distant as the Andromeda galaxy, they present an excellent opportunity for astronomers to study nebulae, star clusters, variable stars, and other key objects in the setting of another galaxy. For example, the Large Magellanic Cloud contains the 30 Doradus complex (also known as the Tarantula Nebula), one of the largest and most luminous groups of supergiant stars known in any galaxy.