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

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.

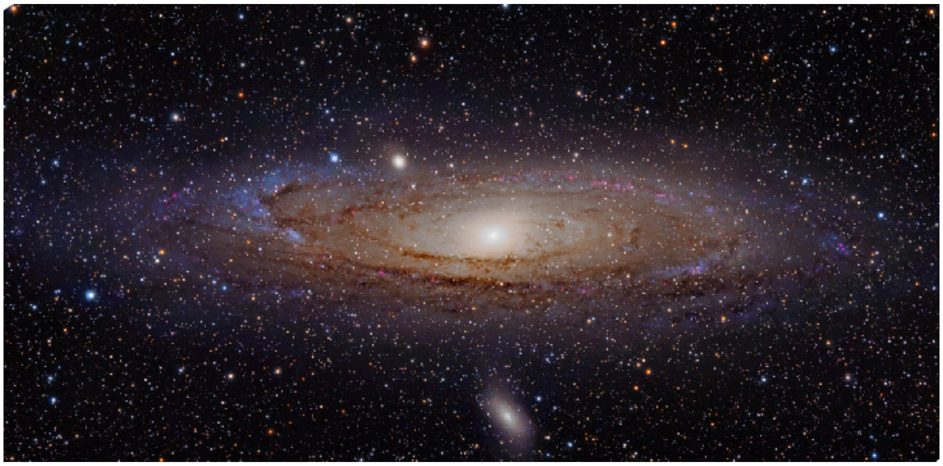

Figure 26.2 Andromeda Galaxy. Also known by its catalog number M31, the Andromeda galaxy is a large spiral galaxy very similar in appearance to, and slightly larger than, our own Galaxy. At a distance of about 2.5 million light-years, Andromeda is the spiral galaxy that is nearest to our own in space. 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 be 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 2.5-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).

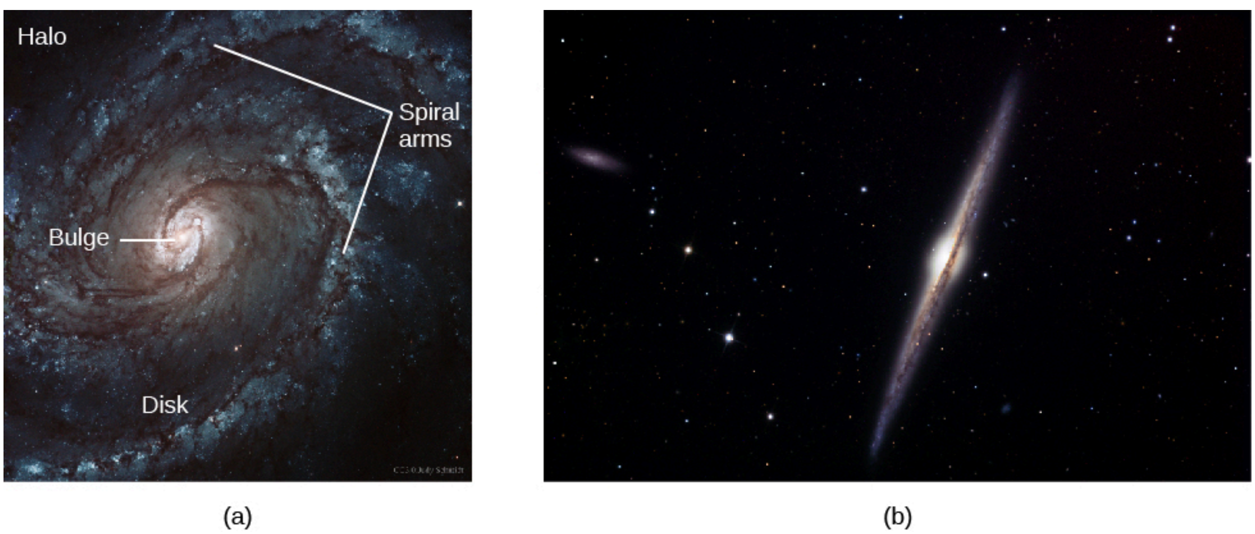

Figure 26.4 Spiral Galaxies. (a) The spiral arms of M100, shown here, are bluer than the rest of the galaxy, indicating young, high-mass stars and star-forming regions. (b) We view this spiral galaxy, NGC 4565, almost exactly edge on, and from this angle, we can see the dust in the plane of the galaxy; 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.

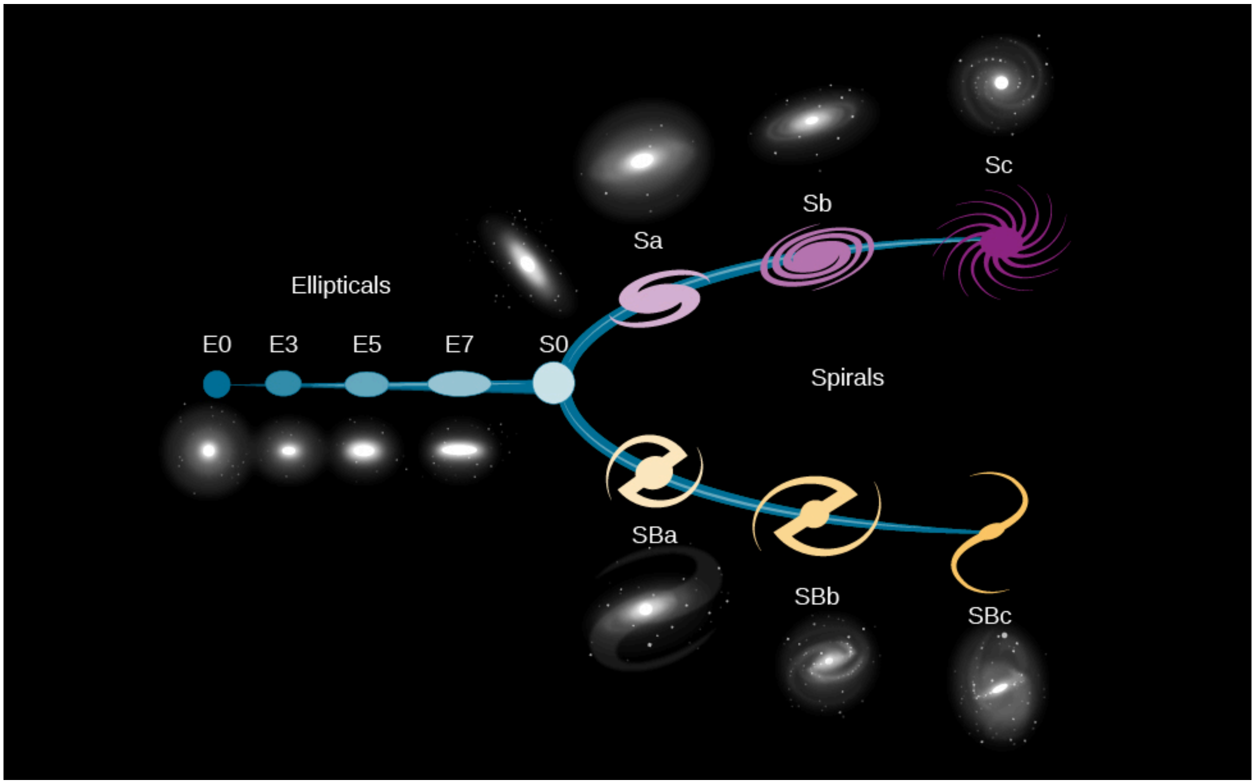

Figure 26.6 Hubble Classification of Galaxies. This figure shows Edwin Hubble's original classification of galaxies. Elliptical galaxies are on the left. On the right, you can see the basic spiral shapes illustrated, alongside images of actual barred and unbarred spirals. (credit: modification of work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

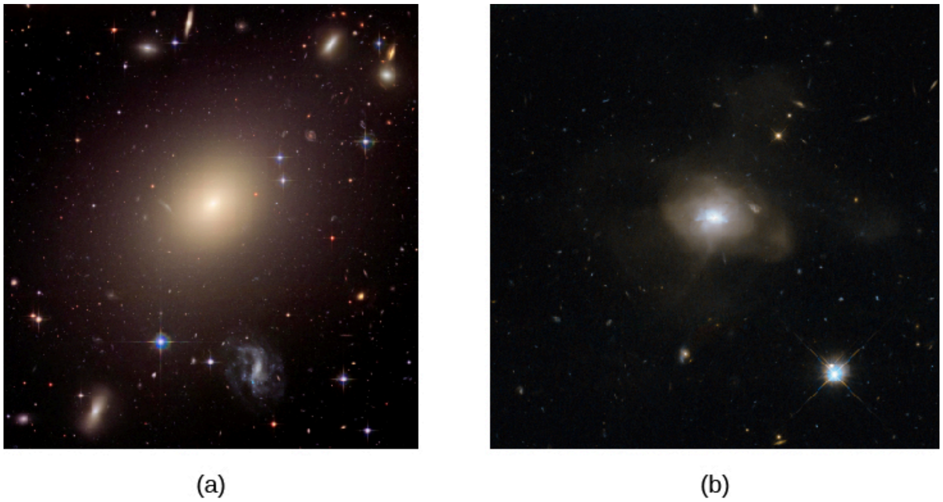

Figure 26.7 Elliptical Galaxies. (a) ESO 325-G004 is a giant elliptical galaxy. Other elliptical galaxies can be seen around the edges of this image. (b) This elliptical galaxy probably originated from the collision of two spiral galaxies. (credit a: modification of work by NASA, ESA, and The Hubble 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_{Sun}. The mass in a giant elliptical can be as large as 10^{13} M_{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.

Figure 26.9 4-Meter Telescope at Cerro Tololo Inter-American Observatory Silhouetted against the Southern Sky. The Milky Way is seen to the right of the dome, and the Large and Small Magellanic Clouds are seen to the left. (credit: Roger Smith/NOAO/AURA/NSF)

The Small Magellanic Cloud is considerably less massive than the Large Magellanic Cloud, and it is six times longer than it is wide. This narrow wisp of material points directly toward our Galaxy like an arrow. The Small Magellanic Cloud was most likely contorted into its current shape through gravitational interactions with the Milky Way. A large trail of debris from this interaction between the Milky Way and the Small Magellanic Cloud has been strewn across the sky and is seen as a series of gas clouds moving at abnormally high velocity, known as the Magellanic Stream. We will see that this kind of interaction between galaxies will help explain the irregular shapes of this whole category of small galaxies,

LINK TO LEARNING

View this beautiful album showcasing the different types of galaxies (https://openstax.org/l/30galaxphohubb) that have been photographed by the Hubble Space Telescope.

Galaxy Evolution

Encouraged by the success of the H-R diagram for stars (see Analyzing Starlight), astronomers studying galaxies hoped to find some sort of comparable scheme, where differences in appearance could be tied to different evolutionary stages in the life of galaxies. Wouldn't it be nice if every elliptical galaxy evolved into a spiral, for example, just as every main-sequence star evolves into a red giant? Several simple ideas of this kind were tried, some by Hubble himself, but none stood the test of time (and observation).

Because no simple scheme for evolving one type of galaxy into another could be found, astronomers then tended to the opposite point of view. For a while, most astronomers thought that all galaxies formed very early in the history of the universe and that the differences between them had to do with the rate of star formation. Ellipticals were those galaxies in which all the interstellar matter was converted rapidly into stars. Spirals were galaxies in which star formation occurred slowly over the entire lifetime of the galaxy. This idea turned out to be too simple as well.

Today, we understand that at least some galaxies have changed types over the billions of years since the universe began. As we shall see in later chapters, collisions and mergers between galaxies may dramatically change spiral galaxies into elliptical galaxies. Even isolated spirals (with no neighbor galaxies in sight) can change their appearance over time. As they consume their gas, the rate of star formation will slow down, and the spiral arms will gradually become less conspicuous. Over long periods, spirals therefore begin to look more like the galaxies at the middle of Figure 26.6 (which astronomers refer to as S0 types).

Over the past several decades, the study of how galaxies evolve over the lifetime of the universe has become one of the most active fields of astronomical research. We will discuss the evolution of galaxies in more detail in The Evolution and Distribution of Galaxies, but let's first see in a little more detail just what different galaxies are like.

26.3 Properties of Galaxies

Learning Objectives

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

- Describe the methods through which astronomers can estimate the mass of a galaxy
- Characterize each type of galaxy by its mass-to-light ratio

The technique for deriving the masses of galaxies is basically the same as that used to estimate the mass of the Sun, the stars, and our own Galaxy. We measure how fast objects in the outer regions of the galaxy are orbiting the center, and then we use this information along with Kepler's third law to calculate how much mass is inside that orbit.

Masses of Galaxies

Astronomers can measure the rotation speed in spiral galaxies by obtaining spectra of either stars or gas, and looking for wavelength shifts produced by the Doppler effect. Remember that the faster something is moving toward or away from us, the greater the shift of the lines in its spectrum. Kepler's law, together with such observations of the part of the Andromeda galaxy that is bright in visible light, for example, show it to have a galactic mass of about 4×10^{11} M_{Sun} (enough material to make 400 billion stars like the Sun).

The total mass of the Andromeda galaxy is greater than this, however, because we have not included the mass of the material that lies beyond its visible edge. Fortunately, there is a handful of objects—such as isolated stars, star clusters, and satellite galaxies—beyond the visible edge that allows astronomers to estimate how much additional matter is hidden out there. Recent studies show that the amount of dark matter beyond the visible edge of Andromeda may be as large as the mass of the bright portion of the galaxy. Indeed, using Kepler's third law and the velocities of its satellite galaxies, the Andromeda galaxy is estimated to have a mass closer to 1.4×10^{12} M_{Sun}. The mass of the Milky Way Galaxy is estimated to be 8.5×10^{11} M_{Sun}, and so our Milky Way is turning out to be somewhat smaller than Andromeda.

Elliptical galaxies do not rotate in a systematic way, so we cannot determine a rotational velocity; therefore, we must use a slightly different technique to measure their mass. Their stars are still orbiting the galactic center, but not in the organized way that characterizes spirals. Since elliptical galaxies contain stars that are billions of years old, we can assume that the galaxies themselves are not flying apart. Therefore, if we can measure the various speeds with which the stars are moving in their orbits around the center of the galaxy, we can calculate how much mass the galaxy must contain in order to hold the stars within it.

In practice, the spectrum of a galaxy is a composite of the spectra of its many stars, whose different motions produce different Doppler shifts (some red, some blue). The result is that the lines we observe from the entire galaxy contain the combination of many Doppler shifts. When some stars provide blueshifts and others provide redshifts, they create a wider or broader absorption or emission feature than would the same lines in a hypothetical galaxy in which the stars had no orbital motion. Astronomers call this phenomenon line broadening. The amount by which each line broadens indicates the range of speeds at which the stars are moving with respect to the center of the galaxy. The range of speeds depends, in turn, on the force of gravity that holds the stars within the galaxies. With information about the speeds, it is possible to calculate the mass of an elliptical galaxy.

Table 26.1 summarizes the range of masses (and other properties) of the various types of galaxies. Interestingly enough, the most and least massive galaxies are ellipticals. On average, irregular galaxies have less mass than spirals.

Characteristics of the Different Types of Galaxies

Characteristic	Spirals	Ellipticals	Irregulars
Mass (M_{Sun})	10^9 to 10^{12}	10^5 to 10^{13}	10^8 to 10^{11}
Diameter (thousands of light-years)	15 to 150	3 to >700	3 to 30
Luminosity (L_{Sun})	10^8 to 10^{11}	10^6 to 10^{11}	10^7 to 2×10^9
Populations of stars	Old and young	Old	Old and young
Interstellar matter	Gas and dust	Almost no dust; little gas	Much gas; some have little dust, some much dust

Table 26.1

Characteristic	Spirals	Ellipticals	Irregulars
Mass-to-light ratio in the visible part	2 to 10	10 to 20	1 to 10
Mass-to-light ratio for total galaxy	100	100	?

Table 26.1

Mass-to-Light Ratio

A useful way of characterizing a galaxy is by noting the ratio of its mass (in units of the Sun's mass) to its light output (in units of the Sun's luminosity). This single number tells us roughly what kind of stars make up most of the luminous population of the galaxy, and it also tells us whether a lot of dark matter is present. For stars like the Sun, the **mass-to-light ratio** is 1 by our definition.

Galaxies are not, of course, composed entirely of stars that are identical to the Sun. The overwhelming majority of stars are less massive and less luminous than the Sun, and usually these stars contribute most of the mass of a system without accounting for very much light. The mass-to-light ratio for low-mass stars is greater than 1 (you can verify this using the data in Table 18.3). Therefore, a galaxy's mass-to-light ratio is also generally greater than 1, with the exact value depending on the ratio of high-mass stars to low-mass stars.

Galaxies in which star formation is still occurring have many massive stars, and their mass-to-light ratios are usually in the range of 1 to 10. Galaxies consisting mostly of an older stellar population, such as ellipticals, in which the massive stars have already completed their evolution and have ceased to shine, have mass-to-light ratios of 10 to 20.

But these figures refer only to the inner, conspicuous parts of galaxies (Figure 26.10). In The Milky Way Galaxy and above, we discussed the evidence for dark matter in the outer regions of our own Galaxy, extending much farther from the galactic center than do the bright stars and gas. Recent measurements of the rotation speeds of the outer parts of nearby galaxies, such as the Andromeda galaxy we discussed earlier, suggest that they too have extended distributions of dark matter around the visible disk of stars and dust. This largely invisible matter adds to the mass of the galaxy while contributing nothing to its luminosity, thus increasing the mass-to-light ratio. If dark invisible matter is present in a galaxy, its mass-to-light ratio can be as high as 100. The two different mass-to-light ratios measured for various types of galaxies are given in Table 26.1.

Figure 26.10 M101, the Pinwheel Galaxy. This galaxy is a face-on spiral at a distance of 21 million light-years. M101 is almost twice the diameter of the Milky Way, and it contains at least 1 trillion stars. (credit: NASA, ESA, K. Kuntz (Johns Hopkins University), F. Bresolin (University of Hawaii), J. Trauger (Jet Propulsion Lab), J. Mould (NOAO), Y.-H. Chu (University of Illinois, Urbana), and STScI)

These measurements of other galaxies support the conclusion already reached from studies of the rotation of our own Galaxy—namely, that most of the material in the universe cannot at present be observed directly in any part of the electromagnetic spectrum. An understanding of the properties and distribution of this invisible matter is crucial to our understanding of galaxies. It's becoming clearer and clearer that, through the gravitational force it exerts, dark matter plays a dominant role in galaxy formation and early evolution. There is an interesting parallel here between our time and the time during which Edwin Hubble was receiving his training in astronomy. By 1920, many scientists were aware that astronomy stood on the brink of important breakthroughs—if only the nature and behavior of the nebulae could be settled with better observations. In the same way, many astronomers today feel we may be closing in on a far more sophisticated understanding of the large-scale structure of the universe—if only we can learn more about the nature and properties of dark matter. If you follow astronomy articles in the news (as we hope you will), you should be hearing more about dark matter in the years to come.

26.4 The Extragalactic Distance Scale

Learning Objectives

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

- Describe the use of variable stars to estimate distances to galaxies
- Explain how standard bulbs and the Tully-Fisher relation can be used to estimate distances to galaxies

To determine many of the properties of a galaxy, such as its luminosity or size, we must first know how far away it is. If we know the distance to a galaxy, we can convert how bright the galaxy appears to us in the sky into its true luminosity because we know the precise way light is dimmed by distance. (The same galaxy 10 times farther away, for example, would look 100 times dimmer.) But the measurement of galaxy distances is one of the most difficult problems in modern astronomy: all galaxies are far away, and most are so distant that we cannot even make out individual stars in them.

For decades after Hubble's initial work, the techniques used to measure galaxy distances were relatively inaccurate, and different astronomers derived distances that differed by as much as a factor of two. (Imagine if the distance between your home or dorm and your astronomy class were this uncertain; it would be difficult to make sure you got to class on time.) In the past few decades, however, astronomers have devised new techniques for measuring distances to galaxies; most importantly, all of them give the same answer to within an accuracy of about 10%. As we will see, this means we may finally be able to make reliable estimates of the size of the universe.

Variable Stars

Before astronomers could measure distances to other galaxies, they first had to establish the scale of cosmic distances using objects in our own Galaxy. We described the chain of these distance methods in Celestial Distances (and we recommend that you review that chapter if it has been a while since you've read it). Astronomers were especially delighted when they discovered that they could measure distances using certain kinds of intrinsically luminous *variable stars*, such as cepheids, which can be seen at very large distances (Figure 26.11).

After the variables in nearby galaxies had been used to make distance measurements for a few decades, Walter Baade showed that there were actually two kinds of cepheids and that astronomers had been unwittingly mixing them up. As a result, in the early 1950s, the distances to all of the galaxies had to be increased by about a factor of two. We mention this because we want you to bear in mind, as you read on, that science is always a study in progress. Our first tentative steps in such difficult investigations are always subject to future revision as our techniques become more reliable.

The amount of work involved in finding cepheids and measuring their periods can be enormous. Hubble, for example, obtained 350 long-exposure photographs of the Andromeda galaxy over a period of 18 years and was able to identify only 40 cepheids. Even though cepheids are fairly luminous stars, they can be detected in only about 30 of the nearest galaxies with the world's largest ground-based telescopes.

As mentioned in Celestial Distances, one of the main projects carried out during the first years of operation of the Hubble Space Telescope was the measurement of cepheids in more distant galaxies to improve the accuracy of the extragalactic distance scale. Recently, astronomers working with the Hubble Space Telescope have extended such measurements out to 108 million light-years—a triumph of technology and determination.

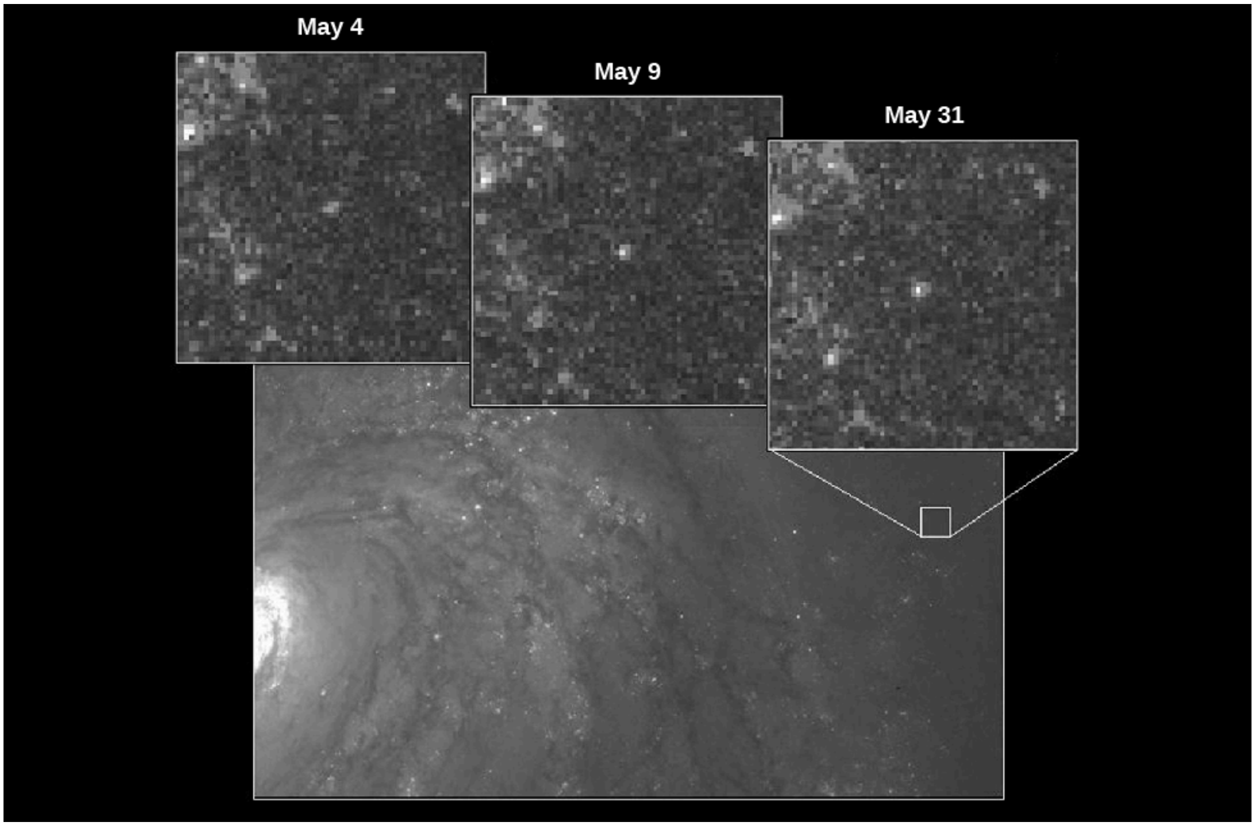

Figure 26.11 Cepheid Variable Star. In 1994, using the Hubble Space Telescope, astronomers were able to make out an individual cepheid variable star in the galaxy M100 and measure its distance to be 56 million light-years. The insets show the star on three different nights; you can see that its brightness is indeed variable. (credit: modification of work by Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA/ESA)

Nevertheless, we can only use cepheids to measure distances within a small fraction of the universe of galaxies. After all, to use this method, we must be able to resolve single stars and follow their subtle variations. Beyond a certain distance, even our finest space telescopes cannot help us do this. Fortunately, there are other ways to measure the distances to galaxies.

Standard Bulbs

We discussed in Celestial Distances the great frustration that astronomers felt when they realized that the stars in general were not standard *bulbs*. If every light bulb in a huge auditorium is a standard 100-watt bulb, then bulbs that look brighter to us must be closer, whereas those that look dimmer must be farther away. If every star were a standard luminosity (or wattage), then we could similarly “read off” their distances based on how bright they appear to us. Alas, as we have learned, neither stars nor galaxies come in one standard-issue luminosity. Nonetheless, astronomers have been searching for objects out there that do act in some way like a standard bulb—that have the same intrinsic (built-in) brightness wherever they are.

A number of suggestions have been made for what sorts of objects might be effective standard bulbs, including the brightest supergiant stars, planetary nebulae (which give off a lot of ultraviolet radiation), and the average globular cluster in a galaxy. One object turns out to be particularly useful: the **type Ia supernova**. These supernovae involve the explosion of a white dwarf in a binary system (see The Evolution of Binary Star Systems) Observations show that supernovae of this type all reach nearly the same luminosity (about 4.5×10^9 L_{Sun}) at maximum light. With such tremendous luminosities, these supernovae have been detected out to a distance of more than 8 billion light-years and are therefore especially attractive to astronomers as a way of determining distances on a large scale (Figure 26.12).

Figure 26.12 Type Ia Supernova. The bright object at the bottom left of center is a type Ia supernova near its peak intensity. The supernova easily outshines its host galaxy. This extreme increase and luminosity help astronomers use Ia supernova as standard bulbs. (credit: NASA, ESA, A. Riess (STScI))

Several other kinds of standard bulbs visible over great distances have also been suggested, including the overall brightness of, for example, giant ellipticals and the brightest member of a galaxy cluster. Type Ia supernovae, however, have proved to be the most accurate standard bulbs, and they can be seen in more distant galaxies than the other types of calibrators. As we will see in the chapter on The Big Bang, observations of this type of supernova have profoundly changed our understanding of the evolution of the universe.

Other Measuring Techniques

Another technique for measuring galactic distances makes use of an interesting relationship noticed in the late 1970s by Brent Tully of the University of Hawaii and Richard Fisher of the National Radio Astronomy Observatory. They discovered that the luminosity of a spiral galaxy is related to its rotational velocity (how fast it spins). Why would this be true?

The more mass a galaxy has, the faster the objects in its outer regions must orbit. A more massive galaxy has more stars in it and is thus more luminous (ignoring dark matter for a moment). Thinking back to our discussion from the previous section, we can say that if the mass-to-light ratios for various spiral galaxies are pretty similar, then we can estimate the luminosity of a spiral galaxy by measuring its mass, and we can estimate its mass by measuring its rotational velocity.

Tully and Fisher used the 21-cm line of cold hydrogen gas to determine how rapidly material in spiral galaxies is orbiting their centers (you can review our discussion of the 21-cm line in Between the Stars: Gas and Dust in Space). Since 21-cm radiation from stationary atoms comes in a nice narrow line, the width of the 21-cm line produced by a whole rotating galaxy tells us the range of orbital velocities of the galaxy's hydrogen gas. The broader the line, the faster the gas is orbiting in the galaxy, and the more massive and luminous the galaxy turns out to be.

It is somewhat surprising that this technique works, since much of the mass associated with galaxies is dark matter, which does not contribute at all to the luminosity but does affect the rotation speed. There is also no obvious reason why the mass-to-light ratio should be similar for all spiral galaxies. Nevertheless, observations of nearer galaxies (where we have other ways of measuring distance) show that measuring the rotational velocity of a galaxy provides an accurate estimate of its intrinsic luminosity. Once we know how luminous the galaxy really is, we can compare the luminosity to the apparent brightness and use the difference to calculate its distance.

While the Tully-Fisher relation works well, it is limited—we can only use it to determine the distance to a spiral galaxy. There are other methods that can be used to estimate the distance to an elliptical galaxy; however, those methods are beyond the scope of our introductory astronomy course.

Table 26.2 lists the type of galaxy for which each of the distance techniques is useful, and the range of distances over which the technique can be applied.

Some Methods for Estimating Distance to Galaxies

Method	Galaxy Type	Approximate Distance Range (millions of light-years)
Planetary nebulae	All	0–70
Cepheid variables	Spiral, irregulars	0–110
Tully-Fisher relation	Spiral	0–300
Type Ia supernovae	All	0–11,000
Redshifts (Hubble’s law)	All	300–13,000

Table 26.2

26.5 The Expanding Universe

Learning Objectives

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

- Describe the discovery that galaxies getting farther apart as the universe evolves
- Explain how to use Hubble’s law to determine distances to remote galaxies
- Describe models for the nature of an expanding universe
- Explain the variation in Hubble’s constant

We now come to one of the most important discoveries ever made in astronomy—the fact that the universe is expanding. Before we describe how the discovery was made, we should point out that the first steps in the study of galaxies came at a time when the techniques of spectroscopy were also making great strides. Astronomers using large telescopes could record the spectrum of a faint star or galaxy on photographic plates, guiding their telescopes so they remained pointed to the same object for many hours and collected more light. The resulting spectra of galaxies contained a wealth of information about the composition of the galaxy and the velocities of these great star systems.

Slipher’s Pioneering Observations

Curiously, the discovery of the expansion of the universe began with the search for Martians and other solar systems. In 1894, the controversial (and wealthy) astronomer Percival Lowell established an observatory in Flagstaff, Arizona, to study the planets and search for life in the universe. Lowell thought that the spiral nebulae might be solar systems in the process of formation. He therefore asked one of the observatory’s young astronomers, Vesto M. Slipher (Figure 26.13), to photograph the spectra of some of the spiral nebulae to see if their spectral lines might show chemical compositions like those expected for newly forming planets.

Figure 26.13 Vesto M. Slipher (1875–1969). Slipher spent his entire career at the Lowell Observatory, where he discovered the large radial velocities of galaxies. (credit: Lowell Observatory)

The Lowell Observatory's major instrument was a 24-inch refracting telescope, which was not at all well suited to observations of faint spiral nebulae. With the technology available in those days, photographic plates had to be exposed for 20 to 40 hours to produce a good spectrum (in which the positions of the lines could reveal a galaxy's motion). This often meant continuing to expose the same photograph over several nights. Beginning in 1912, and making heroic efforts over a period of about 20 years, Slipher managed to photograph the spectra of more than 40 of the spiral nebulae (which would all turn out to be galaxies).

To his surprise, the spectral lines of most galaxies showed an astounding **redshift**. By "redshift" we mean that the lines in the spectra are displaced toward longer wavelengths (toward the red end of the visible spectrum). Recall from the chapter on Radiation and Spectra that a redshift is seen when the source of the waves is moving away from us. Slipher's observations showed that most spirals are racing away at huge speeds; the highest velocity he measured was 1800 kilometers per second.

Only a few spirals—such as the Andromeda and Triangulum Galaxies and M81—all of which are now known to be our close neighbors, turned out to be approaching us. All the other galaxies were moving away. Slipher first announced this discovery in 1914, years before Hubble showed that these objects were other galaxies and before anyone knew how far away they were. No one at the time quite knew what to make of this discovery.

Hubble's Law

The profound implications of Slipher's work became apparent only during the 1920s. Georges Lemaître was a Belgian priest and a trained astronomer. In 1927, he published a paper in French in an obscure Belgian journal in which he suggested that we live in an expanding universe. The title of the paper (translated into English) is "A Homogenous Universe of Constant Mass and Growing Radius Accounting for the Radial Velocity of Extragalactic Nebulae." Lemaître had discovered that Einstein's equations of relativity were consistent with an expanding universe (as had the Russian scientist Alexander Friedmann independently in 1922). Lemaître then went on to use Slipher's data to support the hypothesis that the universe actually is expanding and to estimate the rate of expansion. Initially, scientists paid little attention to this paper, perhaps because the Belgian journal was not widely available.

In the meantime, Hubble was making observations of galaxies with the 2.5-meter telescope on Mt. Wilson, which was then the world's largest. Hubble carried out the key observations in collaboration with a remarkable man, Milton Humason, who dropped out of school in the eighth grade and began his astronomical career by driving a mule train up the trail on Mount Wilson to the observatory (Figure 26.14). In those early days, supplies had to be brought up that way; even astronomers hiked up to the mountaintop for their turns at the telescope. Humason became interested in the work of the astronomers and, after marrying the daughter of the observatory's electrician, took a job as janitor there. After a time, he became a night assistant, helping the astronomers run the telescope and record data. Eventually, he made such a mark that he became a full astronomer at the observatory.

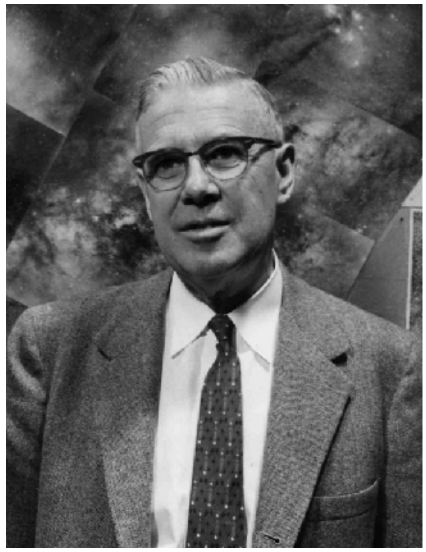

Figure 26.14 Milton Humason (1891–1972). Humason was Hubble's collaborator on the great task of observing, measuring, and classifying the characteristics of many galaxies. (credit: Caltech Archives)

By the late 1920s, Humason was collaborating with Hubble by photographing the spectra of faint galaxies with the 2.5-meter telescope. (By then, there was no question that the spiral nebulae were in fact galaxies.) Hubble had found ways to improve the accuracy of the estimates of distances to spiral galaxies, and he was able to measure much fainter and more distant galaxies than Slipher could observe with his much-smaller telescope. When Hubble laid his own distance estimates next to measurements of the recession velocities (the speed with which the galaxies were moving away), he found something stunning: there was a relationship between distance and velocity for galaxies. *The more distant the galaxy, the faster it was receding from us.*

In 1931, Hubble and Humason jointly published the seminal paper where they compared distances and velocities of remote galaxies moving away from us at speeds as high as 20,000 kilometers per second and were able to show that the recession velocities of galaxies are directly proportional to their distances from us (Figure 26.15), just as Lemaître had suggested.

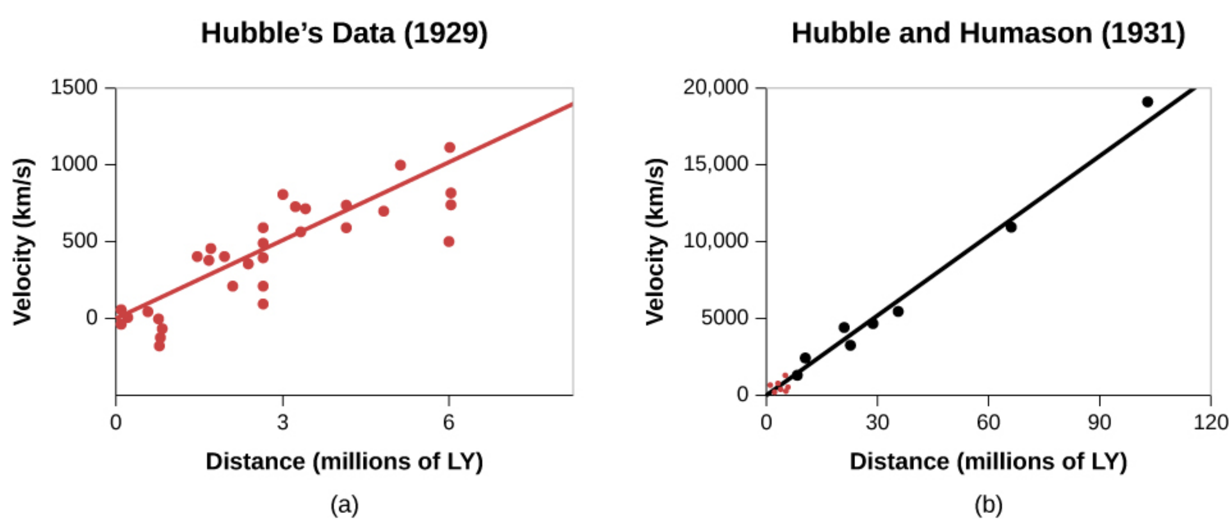

Figure 26.15 Hubble's Law. (a) These data show Hubble's original velocity-distance relation, adapted from his 1929 paper in the *Proceedings of the National Academy of Sciences*. (b) These data show Hubble and Humason's velocity-distance relation, adapted from their 1931 paper in *The Astrophysical Journal*. The red dots at the lower left are the points in the diagram in the 1929 paper.

Comparison of the two graphs shows how rapidly the determination of galactic distances and redshifts progressed in the 2 years between these publications.

We now know that this relationship holds for every galaxy except a few of the nearest ones. Nearly all of the galaxies that are approaching us turn out to be part of the Milky Way's own group of galaxies, which have their own individual motions, just as birds flying in a group may fly in slightly different directions at slightly different speeds even though the entire flock travels through space together.

Written as a formula, the relationship between velocity and distance is

$$v = H \times d$$

where *v* is the velocity, *d* is the distance, and *H* is a number called the **Hubble constant**. This equation is now known as **Hubble's law**.[1]

ASTRONOMY BASICS

Constants of Proportionality

Mathematical relationships such as Hubble's law are pretty common in life. To take a simple example, suppose your college or university hires you to call rich alumni and ask for donations. You are paid $2.50 for each call; the more calls you can squeeze in between studying astronomy and other courses, the more money you take home. We can set up a formula that connects *p*, your pay, and *n*, the number of calls

$$p = A \times n$$

where *A* is the alumni constant, with a value of $2.50. If you make 20 calls, you will earn $2.50 times 20, or $50.

Suppose your boss forgets to tell you what you will get paid for each call. You can calculate the alumni constant that governs your pay by keeping track of how many calls you make and noting your gross pay each week. If you make 100 calls the first week and are paid $250, you can deduce that the constant is $2.50 (in units of dollars per call). Hubble, of course, had no "boss" to tell him what his constant would be—he *had* to calculate its value from the measurements of distance and velocity.

Astronomers express the value of Hubble's constant in units that relate to how they measure speed and distance for galaxies. In this book, we will use kilometers per second per million light-years as that unit. For many years, estimates of the value of the Hubble constant have been in the range of 15 to 30 kilometers per second per million light-years The most recent work appears to be converging on a value near 22 kilometers per second per million light-years If *H* is 22 kilometers per second per million light-years, a galaxy moves away from us at a speed of 22 kilometers per second for every million light-years of its distance. As an example, a galaxy 100 million light-years away is moving away from us at a speed of 2200 kilometers per second.

Hubble's law tells us something fundamental about the universe. Since all but the nearest galaxies appear to be in motion away from us, with the most distant ones moving the fastest, we must be living in an expanding universe. We will explore the implications of this idea shortly, as well as in the final chapters of this text. For now, we will just say that Hubble's observation underlies all our theories about the origin and evolution of the universe.

Hubble's Law and Distances

The regularity expressed in Hubble's law has a built-in bonus: it gives us a new way to determine the distances to remote galaxies. First, we must reliably establish Hubble's constant by measuring both the distance and the

1 In 2020, the International Astronomical Union suggested that it would be more fair to call it the Hubble-Lemaitre law. In telling the history in this textbook, we have acknowledged the role Lemaître played, and we urge our readers to keep his contributions in mind as they read on.

velocity of many galaxies in many directions to be sure Hubble's law is truly a universal property of galaxies. But once we have calculated the value of this constant and are satisfied that it applies everywhere, much more of the universe opens up for distance determination. Basically, if we can obtain a spectrum of a galaxy, we can immediately tell how far away it is.

The procedure works like this. We use the spectrum to measure the speed with which the galaxy is moving away from us. If we then put this speed and the Hubble constant into Hubble's law equation, we can solve for the distance.

EXAMPLE 26.1

Hubble's Law

Hubble's law ($v = H \times d$) allows us to calculate the distance to any galaxy. Here is how we use it in practice.

We have measured Hubble's constant to be 22 km/s per million light-years. This means that if a galaxy is 1 million light-years farther away, it will move away 22 km/s faster. So, if we find a galaxy that is moving away at 18,000 km/s, what does Hubble's law tells us about the distance to the galaxy?

Solution

$$d = \frac{v}{H} = \frac{18{,}000 \text{ km/s}}{\frac{22 \text{ km/s}}{1 \text{ million light-years}}} = \frac{18{,}000}{22} \times \frac{1 \text{ million light-years}}{1} = 818 \text{ million light-years}$$

Note how we handled the units here: the km/s in the numerator and denominator cancel, and the factor of million light-years in the denominator of the constant must be divided correctly before we get our distance of 818 million light-years.

Check Your Learning

Using 22 km/s/million light-years for Hubble's constant, what recessional velocity do we expect to find if we observe a galaxy at 500 million light-years?

Answer:

$$v = d \times H = 500 \text{ million light-years} \times \frac{22 \text{ km/s}}{1 \text{ million light-years}} = 11{,}000 \text{ km/s}$$

Variation of Hubble's Constant

The use of redshift is potentially a very important technique for determining distances because as we have seen, most of our methods for determining galaxy distances are limited to approximately the nearest few hundred million light-years (and they have large uncertainties at these distances). The use of Hubble's law as a distance indicator requires only a spectrum of a galaxy and a measurement of the Doppler shift, and with large telescopes and modern spectrographs, spectra can be taken of extremely faint galaxies.

But, as is often the case in science, things are not so simple. This technique works if, and only if, the Hubble constant has been truly constant throughout the entire life of the universe. When we observe galaxies billions of light-years away, we are seeing them as they were billions of years ago. What if the Hubble "constant" was different billions of years ago? Before 1998, astronomers thought that, although the universe is expanding, the expansion should be slowing down, or decelerating, because the overall gravitational pull of all matter in the universe would have a dominant, measureable effect. If the expansion is decelerating, then the Hubble constant should be decreasing over time.

The discovery that type Ia supernovae are standard bulbs gave astronomers the tool they needed to observe extremely distant galaxies and measure the rate of expansion billions of years ago. The results were completely unexpected. It turns out that the expansion of the universe is *accelerating* over time! What makes this result so astounding is that there is no way that existing physical theories can account for this observation. While a decelerating universe could easily be explained by gravity, there was no force or property in the universe known to astronomers that could account for the acceleration. In The Big Bang chapter, we will look in more detail at the observations that led to this totally unexpected result and explore its implications for the ultimate fate of the universe.

In any case, if the Hubble constant is not really a constant when we look over large spans of space and time, then the calculation of galaxy distances using the Hubble constant won't be accurate. As we shall see in the chapter on The Big Bang, the accurate calculation of distances requires a model for how the Hubble constant has changed over time. The farther away a galaxy is (and the longer ago we are seeing it), the more important it is to include the effects of the change in the Hubble constant. For galaxies within a few billion light-years, however, the assumption that the Hubble constant is indeed constant gives good estimates of distance.

Models for an Expanding Universe

At first, thinking about Hubble's law and being a fan of the work of Copernicus and Harlow Shapley, you might be shocked. Are all the galaxies really moving *away from us*? Is there, after all, something special about our position in the universe? Worry not; the fact that galaxies are receding from us and that more distant galaxies are moving away more rapidly than nearby ones shows only that the universe is expanding uniformly.

A uniformly expanding universe is one that is expanding at the same rate everywhere. In such a universe, we and all other observers, no matter where they are located, must observe a proportionality between the velocities and distances of equivalently remote galaxies. (Here, we are ignoring the fact that the Hubble constant is not constant over all time, but if at any given time in the evolution of the universe the Hubble constant has the same value everywhere, this argument still works.)

To see why, first imagine a ruler made of stretchable rubber, with the usual lines marked off at each centimeter. Now suppose someone with strong arms grabs each end of the ruler and slowly stretches it so that, say, it doubles in length in 1 minute (Figure 26.16). Consider an intelligent ant sitting on the mark at 2 centimeters—a point that is not at either end nor in the middle of the ruler. He measures how fast other ants, sitting at the 4-, 7-, and 12-centimeter marks, move away from him as the ruler stretches.

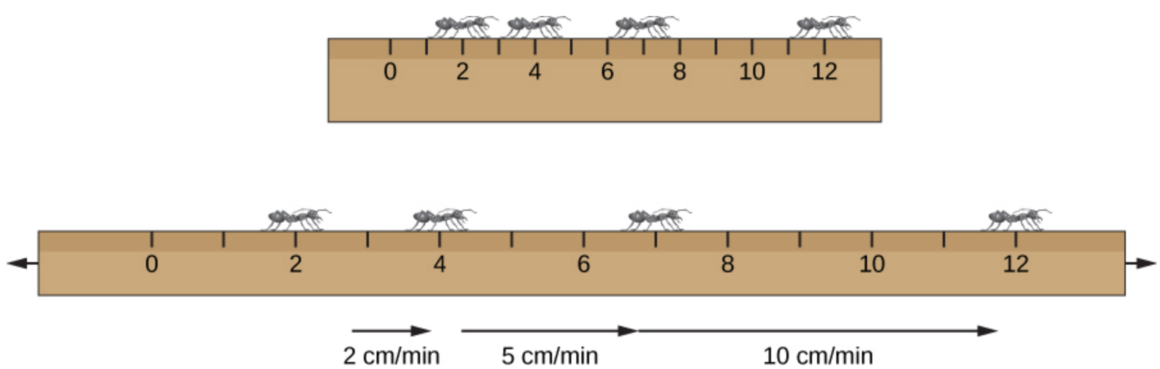

Figure 26.16 Stretching a Ruler. Ants on a stretching ruler see other ants move away from them. The speed with which another ant moves away is proportional to its distance.

The ant at 4 centimeters, originally 2 centimeters away from our ant, has doubled its distance in 1 minute; it therefore moved away at a speed of 2 centimeters per minute. The ant at the 7-centimeters mark, which was originally 5 centimeters away from our ant, is now 10 centimeters away; it thus had to move at 5 centimeters per minute. The one that started at the 12-centimeters mark, which was 10 centimeters away from the ant doing the counting, is now 20 centimeters away, meaning it must have raced away at a speed of 10 centimeters per minute. Ants at different distances move away at different speeds, and their speeds are proportional to their distances (just as Hubble's law indicates for galaxies). Yet, notice in our example that all the ruler was doing was stretching uniformly. Also, notice that none of the ants were actually moving of their own accord, it was the stretching of the ruler that moved them apart.

Now let's repeat the analysis, but put the intelligent ant on some other mark—say, on 7 or 12 centimeters. We discover that, as long as the ruler stretches uniformly, this ant also finds every other ant moving away at a speed proportional to its distance. In other words, the kind of relationship expressed by Hubble's law can be explained by a uniform stretching of the "world" of the ants. And all the ants in our simple diagram will see the other ants moving away from them as the ruler stretches.

For a three-dimensional analogy, let's look at the loaf of raisin bread in Figure 26.17. The chef has accidentally put too much yeast in the dough, and when she sets the bread out to rise, it doubles in size during the next hour, causing all the raisins to move farther apart. On the figure, we again pick a representative raisin (that is not at the edge or the center of the loaf) and show the distances from it to several others in the figure (before and after the loaf expands).

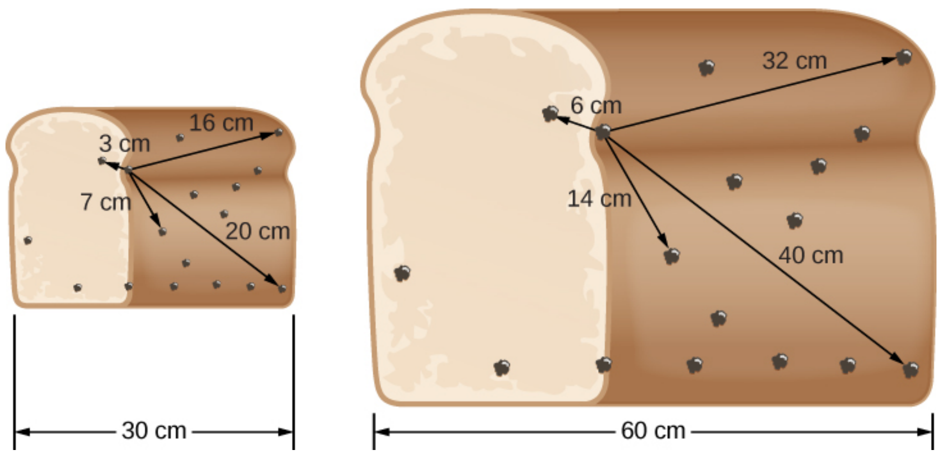

Figure 26.17 Expanding Raisin Bread. As the raisin bread rises, the raisins "see" other raisins moving away. More distant raisins move away faster in a uniformly expanding bread.

Measure the increases in distance and calculate the speeds for yourself on the raisin bread, just like we did for the ruler. You will see that, since each distance doubles during the hour, each raisin moves away from our selected raisin at a speed proportional to its distance. The same is true no matter which raisin you start with.

Our two analogies are useful for clarifying our thinking, but you must not take them literally. On both the ruler and the raisin bread, there are points that are at the end or edge. You can use these to pinpoint the middle of the ruler and the loaf. While our models of the universe have some resemblance to the properties of the ruler and the loaf, the universe has no boundaries, no edges, and no center (all mind-boggling ideas that we will discuss in a later chapter).

What is useful to notice about both the ants and the raisins is that they themselves did not "cause" their motion. It isn't as if the raisins decided to take a trip away from each other and then hopped on a hoverboard to get away. No, in both our analogies, it was the stretching of the medium (the ruler or the bread) that moved the ants or the raisins farther apart. In the same way, we will see in The Big Bang chapter that the galaxies don't have rocket motors propelling them away from each other. Instead, they are passive participants in the *expansion of space*. As space stretches, the galaxies are carried farther and farther apart much as the ants and the raisins were. (If this notion of the "stretching" of space surprises or bothers you, now would be a good time to review the information about spacetime in Black Holes and Curved Spacetime. We will discuss these ideas further as our discussion broadens from galaxies to the whole universe.)

The expansion of the universe, by the way, does not imply that the individual galaxies and clusters of galaxies themselves are expanding. Neither raisins nor the ants in our analogy grow in size as the loaf expands. Similarly, gravity holds galaxies and clusters of galaxies together, and they get farther away from each other—without themselves changing in size—as the universe expands.

Key Terms

elliptical galaxy a galaxy whose shape is an ellipse and that contains no conspicuous interstellar material
Hubble constant a constant of proportionality in the law relating the velocities of remote galaxies to their distances
Hubble's law a rule that the radial velocities of remote galaxies are proportional to their distances from us
irregular galaxy a galaxy without any clear symmetry or pattern; neither a spiral nor an elliptical galaxy
mass-to-light ratio the ratio of the total mass of a galaxy to its total luminosity, usually expressed in units of solar mass and solar luminosity; the mass-to-light ratio gives a rough indication of the types of stars contained within a galaxy and whether or not substantial quantities of dark matter are present
redshift when lines in the spectra are displaced toward longer wavelengths (toward the red end of the visible spectrum)
spiral galaxy a flattened, rotating galaxy with pinwheel-like arms of interstellar material and young stars, winding out from its central bulge
type Ia supernova a supernova formed by the explosion of a white dwarf in a binary system and reach a luminosity of about 4.5×10^9 L_{Sun}; can be used to determine distances to galaxies on a large scale

Summary

26.1 The Discovery of Galaxies

Faint star clusters, clouds of glowing gas, and galaxies all appeared as faint patches of light (or nebulae) in the telescopes available at the beginning of the twentieth century. It was only when Hubble measured the distance to the Andromeda galaxy using cepheid variables with the giant 2.5-meter reflector on Mount Wilson in 1924 that the existence of other galaxies similar to the Milky Way in size and content was established.

26.2 Types of Galaxies

The majority of bright galaxies are either spirals or ellipticals. Spiral galaxies contain both old and young stars, as well as interstellar matter, and have typical masses in the range of 10^9 to 10^{12} M_{Sun}. Our own Galaxy is a large spiral. Ellipticals are spheroidal or slightly elongated systems that consist almost entirely of old stars, with very little interstellar matter. Elliptical galaxies range in size from giants, more massive than any spiral, down to dwarfs, with masses of only about 10^6 M_{Sun}. Dwarf ellipticals are probably the most common type of galaxy in the nearby universe. A small percentage of galaxies with more disorganized shapes are classified as irregulars. Galaxies may change their appearance over time due to collisions with other galaxies or by a change in the rate of star formation.

26.3 Properties of Galaxies

The masses of spiral galaxies are determined from measurements of their rates of rotation. The masses of elliptical galaxies are estimated from analyses of the motions of the stars within them. Galaxies can be characterized by their mass-to-light ratios. The luminous parts of galaxies with active star formation typically have mass-to-light ratios in the range of 1 to 10; the luminous parts of elliptical galaxies, which contain only old stars, typically have mass-to-light ratios of 10 to 20. The mass-to-light ratios of whole galaxies, including their outer regions, are as high as 100, indicating the presence of a great deal of dark matter.

26.4 The Extragalactic Distance Scale

Astronomers determine the distances to galaxies using a variety of methods, including the period-luminosity relationship for cepheid variables; objects such as type Ia supernovae, which appear to be standard bulbs; and the Tully-Fisher relation, which connects the line broadening of 21-cm radiation to the luminosity of spiral galaxies. Each method has limitations in terms of its precision, the kinds of galaxies with which it can be used, and the range of distances over which it can be applied.

26.5 The Expanding Universe

The universe is expanding. Observations show that the spectral lines of distant galaxies are redshifted, and that their recession velocities are proportional to their distances from us, a relationship known as Hubble's law. The rate of recession, called the Hubble constant, is approximately 22 kilometers per second per million light-years. We are not at the center of this expansion: an observer in any other galaxy would see the same pattern of expansion that we do. The expansion described by Hubble's law is best understood as a stretching of space.

For Further Exploration

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Websites

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Cosmic Times 1929: http://cosmictimes.gsfc.nasa.gov/online_edition/1929Cosmic/index.html (http://cosmictimes.gsfc.nasa.gov/online_edition/1929Cosmic/index.html). NASA project explaining Hubble's work and surrounding discoveries as if you were reading newspaper articles.

Edwin Hubble: Biography: https://www.nasa.gov/content/about-story-edwin-hubble (https://www.nasa.gov/content/about-story-edwin-hubble). Concise biography from the people at the Hubble Space Telescope.

Edwin Hubble: http://apod.nasa.gov/diamond_jubilee/d_1996/sandage_hubble.html (http://apod.nasa.gov/diamond_jubilee/d_1996/sandage_hubble.html). An article on the life and work of Hubble by his student and successor, Allan Sandage. A bit technical in places, but giving a real picture of the man and the science.

International Astronomical Union resolution to call Hubble Law the Hubble-Lemaître Law (with background information): https://www.iau.org/news/pressreleases/detail/iau1812/ (https://www.iau.org/news/pressreleases/detail/iau1812/).

NASA Science: Introduction to Galaxies: http://science.nasa.gov/astrophysics/focus-areas/what-are-galaxies/ (http://science.nasa.gov/astrophysics/focus-areas/what-are-galaxies/). A brief overview with links to other pages, and recent Hubble Space Telescope discoveries.

National Optical Astronomy Observatories Gallery of Galaxies: https://www.noao.edu/image_gallery/galaxies.html (https://www.noao.edu/image_gallery/galaxies.html). A collection of images and information about galaxies and galaxy groups of different types. Another impressive archive can be found at the European Southern Observatory site: https://www.eso.org/public/images/archive/category/galaxies/ (https://www.eso.org/public/images/archive/category/galaxies/).

Sloan Digital Sky Survey: Introduction to Galaxies: http://skyserver.sdss.org/dr1/en/astro/galaxies/galaxies.asp (http://skyserver.sdss.org/dr1/en/astro/galaxies/galaxies.asp). Another brief overview.

Universe Expansion: https://hubblesite.org/contents/news-releases/1999/news-1999-19.html (https://hubblesite.org/contents/news-releases/1999/news-1999-19.html). The background material here provides a nice chronology of how we discovered and measured the expansion of the universe.

Videos

Edwin Hubble (Hubblecast Episode 89): http://www.spacetelescope.org/videos/hubblecast89a/ (http://www.spacetelescope.org/videos/hubblecast89a/). (5:59).

Galaxies: https://www.youtube.com/watch?v=I82ADyJC7wE (https://www.youtube.com/watch?v=I82ADyJC7wE). An introduction.

Hubble's Views of the Deep Universe: https://www.youtube.com/watch?v=argR2U15w-M (https://www.youtube.com/watch?v=argR2U15w-M). A 2015 public talk by Brandon Lawton of the Space Telescope Science Institute about galaxies and beyond (1:26:20).

Collaborative Group Activities

A. Throughout much of the last century, the 100-inch telescope on Mt. Wilson (completed in 1917) and the 200-inch telescope on Palomar Mountain (completed in 1948) were the only ones large enough to obtain spectra of faint galaxies. Only a handful of astronomers (all male—since, until the 1960s, women were not given time on these two telescopes) were allowed to use these facilities, and in general the observers did not compete with each other but worked on different problems. Now there are many other telescopes, and several different groups do often work on the same problem. For example, two different groups have independently developed the techniques for using supernovae to determine the distances to galaxies at high redshifts. Which approach do you think is better for the field of astronomy? Which is more cost effective? Why?

B. A distant relative, whom you invite to dinner so you can share all the exciting things you have learned in your astronomy class, says he does not believe that other galaxies are made up of stars. You come back to your group and ask them to help you respond. What kinds of measurements would you make to show that other galaxies are composed of stars?

C. Look at Figure 26.1 with your group. What does the difference in color between the spiral arms and the bulge of Andromeda tell you about the difference in the types of stars that populate these two regions of the galaxy? Which side of the galaxy is closer to us? Why?

D. What is your reaction to reading about the discovery of the expanding universe? Discuss how the members of the group feel about a universe "in motion." Einstein was not comfortable with the notion of a universe that had some overall movement to it, instead of being at rest. He put a kind of "fudge factor" into his equations of general relativity for the universe as a whole to keep it from moving (although later, hearing about Hubble and Humason's work, he called it "the greatest blunder" he ever made). Do you share Einstein's original sense that this is not the kind of universe you feel comfortable with? What do you think could have caused space to be expanding?

E. In science fiction, characters sometimes talk about visiting other galaxies. Discuss with your group how realistic this idea is. Even if we had fast spaceships (traveling close to the speed of light, the speed limit of the universe) how likely are we to be able to reach another galaxy? Why?

F. Despite his son's fascination with astronomy in college, Edwin Hubble's father did not want him to go into astronomy as a profession. He really wanted his son to be a lawyer and pushed him hard to learn the law when he won a fellowship to study abroad. Hubble eventually defied his father and went into astronomy, becoming, as you learned in this chapter, one of the most important astronomers of all time. His dad didn't live to see his son's remarkable achievements. Do you think he would have reconciled himself to his son's career choice if he had? Do you or does anyone in your group or among your friends have to face a choice between the passion in your heart and what others want you to do? Discuss how people in college today are dealing with such choices.

Exercises

Review Questions

1. Describe the main distinguishing features of spiral, elliptical, and irregular galaxies.

2. Why did it take so long for the existence of other galaxies to be established?

3. Explain what the mass-to-light ratio is and why it is smaller in spiral galaxies with regions of star formation than in elliptical galaxies.

4. If we now realize dwarf ellipticals are the most common type of galaxy, why did they escape our notice for so long?

5. What are the two best ways to measure the distance to a nearby spiral galaxy, and how would it be measured?

6. What are the two best ways to measure the distance to a distant, isolated spiral galaxy, and how would it be measured?

7. Why is Hubble's law considered one of the most important discoveries in the history of astronomy?

8. What does it mean to say that the universe is expanding? What is expanding? For example, is your astronomy classroom expanding? Is the solar system? Why or why not?

9. Was Hubble's original estimate of the distance to the Andromeda galaxy correct? Explain.

10. Does an elliptical galaxy rotate like a spiral galaxy? Explain.

11. Why does the disk of a spiral galaxy appear dark when viewed edge on?

12. What causes the largest mass-to-light ratio: gas and dust, dark matter, or stars that have burnt out?

13. What is the most useful standard bulb method for determining distances to galaxies?

14. When comparing two isolated spiral galaxies that have the same apparent brightness, but rotate at different rates, what can you say about their relative luminosity?

15. If all distant galaxies are expanding away from us, does this mean we're at the center of the universe?

16. Is the Hubble constant actually constant?

Thought Questions

17. Where might the gas and dust (if any) in an elliptical galaxy come from?

18. Why can we not determine distances to galaxies by the same method used to measure the parallaxes of stars?

19. Which is redder—a spiral galaxy or an elliptical galaxy?

20. Suppose the stars in an elliptical galaxy all formed within a few million years shortly after the universe began. Suppose these stars have a range of masses, just as the stars in our own galaxy do. How would the color of the elliptical change over the next several billion years? How would its luminosity change? Why?

21. Starting with the determination of the size of Earth, outline a sequence of steps necessary to obtain the distance to a remote cluster of galaxies. (Hint: Review the chapter on Celestial Distances.)

22. Suppose the Milky Way Galaxy were truly isolated and that no other galaxies existed within 100 million light-years. Suppose that galaxies were observed in larger numbers at distances greater than 100 million light-years. Why would it be more difficult to determine accurate distances to those galaxies than if there were also galaxies relatively close by?

23. Suppose you were Hubble and Humason, working on the distances and Doppler shifts of the galaxies. What sorts of things would you have to do to convince yourself (and others) that the relationship you were seeing between the two quantities was a real feature of the behavior of the universe? (For example, would data from two galaxies be enough to demonstrate Hubble's law? Would data from just the nearest galaxies—in what astronomers call "the Local Group"—suffice?)

24. What does it mean if one elliptical galaxy has broader spectrum lines than another elliptical galaxy?

25. Based on your analysis of galaxies in Table 26.1, is there a correlation between the population of stars and the quantity of gas or dust? Explain why this might be.

26. Can a higher mass-to-light ratio mean that there is gas and dust present in the system that is being analyzed?

Figuring for Yourself

27. According to Hubble's law, what is the recessional velocity of a galaxy that is 10^8 light-years away from us? (Assume a Hubble constant of 22 km/s per million light-years.)

28. A cluster of galaxies is observed to have a recessional velocity of 60,000 km/s. Find the distance to the cluster. (Assume a Hubble constant of 22 km/s per million light-years.)

29. Suppose we could measure the distance to a galaxy using one of the distance techniques listed in Table 26.2 and it turns out to be 200 million light-years. The galaxy's redshift tells us its recessional velocity is 5000 km/s. What is the Hubble constant?

30. Calculate the mass-to-light ratio for a globular cluster with a luminosity of 10^6 L_{Sun} and 10^5 stars. (Assume that the average mass of a star in such a cluster is 1 M_{Sun}.)

31. Calculate the mass-to-light ratio for a luminous star of 100 M_{Sun} having the luminosity of 10^6 L_{Sun}.