Chapter 1: Our Place in the Universe

LEARNING GOALS

1.1 A Modern View of the Universe
- What is our physical place in the universe?
- What are our cosmic origins and why do we say that we are made of “star stuff”?
- Why does looking into space mean looking back in time?

1.2 The Scale of the Universe
- What does our solar system look like when viewed to scale?
- How far away and how numerous are the stars?
- How do human time scales compare to the age of the universe?

1.3 Spaceship Earth
- What are the basic motions of spaceship Earth?
- How do we know that the universe is expanding?

1.4 The Human Adventure of Astronomy
- How is astronomy interwoven with other aspects of human society?

We succeeded in taking [a picture of Earth from the outskirts of our solar system], and, if you look at it, you see a dot. That's here. That's home. That's us. On it, everyone you ever heard of, every human being who ever lived, lived out their lives. The aggregate of all our joys and sufferings, thousands of confident religions, ideologies and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilizations, every king and peasant, every young couple in love, every hopeful child, every mother and father, every inventor and explorer, every teacher of morals, every corrupt politician, every superstar,
every supreme leader, every saint and sinner in the history of our species, lived
there on a mote of dust, suspended in a sunbeam.

-Carl Sagan

Far from city lights on a clear night, you can gaze upward at a sky filled with stars.
If you lie back and watch for a few hours, you will observe the stars marching
steadily across the sky. Confronted by the seemingly infinite heavens, you might
wonder how Earth and the universe came to be. With these thoughts, you will be
sharing an experience common to humans around the world and in thousands of
generations past.

Modern science offers answers to many of our fundamental questions about the
universe and our place within it. We now know the basic content and scale of the
universe. We know the age of Earth and the approximate age of the universe. And,
although much remains to be discovered, we are rapidly learning how the simple
constituents of the early universe developed into the incredible diversity of life on
Earth.

In this first chapter, we will survey the content and history of the universe, the scale
of the universe, and the motions of Earth in our universe. We'll develop a “big
picture” perspective on our place in the universe that will provide a base on which
we can build a deeper understanding in the rest of the book.

1.1 A Modern View of the Universe

If you observe the sky carefully, you can see why most of our ancestors believed
that the heavens revolved about Earth. The Sun, Moon, planets, and stars appear
to circle around our sky each day, and we cannot feel the constant motion of Earth
as it rotates on its axis and orbits the Sun. Thus, it seems quite natural to assume
that we live in an Earth-centered, or geocentric, universe.

Nevertheless, we now know that Earth is a planet orbiting a rather average star in
a vast cosmos. (In astronomy, the term cosmos is synonymous with universe.) The
historical path to this knowledge was long and complex, involving the dedicated
intellectual efforts of thousands of individuals. In later chapters, we'll encounter
many of these individuals and explore how their discoveries changed human
understanding of the universe. We'll see that many ancient beliefs made a lot of
sense and changed only when people were confronted by strong evidence to the
contrary. We'll also see how the process of science has enabled us to acquire this
evidence and thereby discover that we are connected to the stars in ways our
ancestors never imagined.

First, however, it's useful to have at least a general picture of the universe as we
know it today. This big picture will make it easier for you to understand the
historical development of astronomy, the evidence for our modern ideas, and the
mysteries that remain. Let's begin by examining what modern astronomy has to say
about our cosmic location and origins.
1.2 The Scale of the Universe

Scale of the Universe Tutorial, Lessons 1–3
(This feature requires a live internet connection.)

The numbers we've given in our description of the size and age of the universe probably have little meaning for you—after all, they are literally astronomical. In this section, we will try to give meaning to incredible cosmic distances and times.

Virtual Tour of the Solar System

1.3 Spaceship Earth

The next step in our “big picture” overview is getting a sense of motion in the universe. Wherever you are as you read this book, you probably have the feeling that you're “just sitting here.” Nothing could be further from the truth. In fact, you are being spun in circles as Earth rotates, you are racing around the Sun in Earth's orbit, and you are careening through the cosmos in the Milky Way Galaxy. In the words of noted inventor and philosopher R. Buckminster Fuller (1895–1983), you are a traveler on spaceship Earth.

1.4 The Human Adventure of Astronomy

In a relatively few pages, we've laid out a fairly complete overview of our modern scientific ideas about the universe. But our goal in this book is not for you simply to be able to recite these ideas. Rather, it is to help you understand the evidence supporting them and the extraordinary story of how they developed.

Astronomy is a human adventure in the sense that it affects virtually everyone—even those who have never looked at the sky—because the development of astronomy has been so deeply intertwined with the development of civilization as a whole. Revolutions in astronomy have gone hand in hand with the revolutions in science and technology that have shaped modern life.

Witness the repercussions of the Copernican revolution, which changed our view of Earth from being the center of the universe to being just one planet orbiting the Sun. This revolution, which we will discuss further in Chapter 3, began when Copernicus published his idea of a Sun-centered solar system in 1543. Three subsequent figures—Tycho Brahe, Johannes Kepler, and Galileo—provided the key evidence that eventually led to wide acceptance of the Copernican idea. The revolution culminated with Isaac Newton's uncovering of the laws of motion and gravity. Newton's work, in turn, became the foundation of physics that helped fuel the industrial revolution.
More recently, the development of space travel and the computer revolution have helped fuel tremendous progress in astronomy. We've learned a lot about our solar system by sending probes to the planets, and many of our most powerful observatories, including the Hubble Space Telescope, reside in space. On the ground, computer design and control have led to tremendous growth in the size and power of telescopes, particularly in the past decade.

Many of these efforts, along with the achievements they spawned, have led to profound social change. The most famous example involved Galileo, whom the Vatican put under house arrest in 1633 for his claims that Earth orbits the Sun. Although the Church soon recognized that Galileo was right, he was formally vindicated only with a statement by Pope John Paul II in 1992. In the meantime, his case spurred great debate in religious circles and had a profound influence on both theological and scientific thinking.

As you progress through this book and learn about astronomical discovery, try to keep in mind the context of the human adventure. You will then be learning not just about a science, but about one of the great forces that have helped shape our modern world. This context will also lead you to think about how the many astronomical mysteries that remain—such as the makeup of dark matter, the events of the first instant of the Big Bang, and the question of life beyond Earth—may influence our future.

What would it mean to us if we were ever to learn the complete story of our cosmic origins? How would our view of Earth be changed if we came to learn that Earth-like planets are common or exceedingly rare? Only time may answer these questions, but the chapters ahead give you the foundation you need to understand how we changed from a primitive people looking at patterns in the night sky to a civilization capable of asking deep questions about our existence.

☐ Our Cosmic Address
Take a look at Figure 1.1. Going counterclockwise from Earth, this painting illustrates the basic levels of structure that describe what we might call our “cosmic address.”

Figure 1.1
This painting illustrates our cosmic address. Earth is one of nine planets orbiting the Sun in our solar system. Our solar system is one of more than 100 billion star systems in the Milky Way Galaxy. Our galaxy is one of the two largest of about 40 galaxies in the Local Group. The Local Group lies near the outskirts of the Local Supercluster. The Local Supercluster is one piece of the complex, large-scale structure traced by galaxies throughout the universe. Earth is a planet in our solar system, which consists of the Sun and all the objects that orbit it: nine planets and their moons, the chunks of rock we call asteroids, the balls of ice we call comets, and countless tiny particles of interplanetary dust.
Our Sun is a star, just like the stars we see in our night sky. The Sun and all the stars we can see with the naked eye make up only a small part of a huge, disk-shaped collection of stars called the **Milky Way Galaxy**. A galaxy is a great island of stars in space, containing from a few hundred million to a trillion or more stars. The Milky Way Galaxy is relatively large, containing more than 100 billion stars. Our solar system is located a little over halfway from the galactic center to the edge of the galactic disk.

Some galaxies are fairly isolated, but many others congregate in groups. Our Milky Way, for example, is one of the two largest galaxies among about 40 galaxies in the **Local Group**. Groups of galaxies with more than a few dozen members are often called **galaxy clusters**.

### Basic Astronomical Objects, Units, and Motions

This box summarizes a few key astronomical definitions introduced in this chapter and used throughout the book.

#### Basic Astronomical Objects

- **star** Our Sun and other ordinary stars are large, glowing balls of gas that generate heat and light through nuclear fusion in their cores. (The term star is also applied to objects that are in the process of becoming true stars, such as protostars, and to the remains of stars that have died, such as neutron stars.)

- **planet** A moderately large object that orbits a star. Planets may be rocky, icy, or gaseous in composition, and they shine primarily by reflecting light from their star. Astronomers sometimes disagree about what counts as a planet, because there are no official minimum or maximum sizes. For example, some astronomers argue that Pluto is too small to count as a planet. On the large side, astronomers disagree about whether an object a couple dozen times the size of Jupiter should be called a very large planet or a “failed star” (such as a brown dwarf [Section 17.2]).

- **moon** (or **satellite**) An object that orbits a planet. The term satellite is also used more generally to refer to any object orbiting another object.

- **asteroid** A relatively small and rocky object that orbits a star. Asteroids are sometimes called minor planets because they orbit much like planets but are smaller than anything we consider to be a true planet.

- **comet** A relatively small and icy object that orbits a star.

#### Collections of Astronomical Objects

- **solar system** Our solar system consists of the Sun and all the material that orbits it, including the planets. The term solar system technically refers only to our own star system (because solar means “of the Sun”), but it is sometimes applied to other star systems.

- **star system** A star (sometimes more than one star) and any planets and other materials that orbit it. (Roughly half of all star systems contain two or
more stars.)

- **galaxy** A great island of stars in space, containing from a few hundred million to a trillion or more stars, all held together by gravity and orbiting a common center.

- **cluster** (or group) of galaxies A collection of galaxies bound together by gravity. Small collections (up to a few dozen galaxies) are generally called groups, with the term cluster reserved for larger collections of galaxies.

- **supercluster** A gigantic region of space where many individual galaxies and many groups and clusters of galaxies are packed closer together than elsewhere in the universe.

- **universe** (or cosmos) The sum total of all matter and energy, that is, everything within and between all galaxies.

- **observable universe** The portion of the entire universe that, at least in principle, can be seen from Earth. The observable universe is probably only a tiny portion of the entire universe.

**Astronomical Distance Units**

- **astronomical unit (AU)** The average distance between Earth and the Sun, which is about 150 million kilometers. (More technically, 1 AU is the length of the semimajor axis of Earth's orbit.)

- **light-year** The distance that light can travel in 1 year, which is about 9.46 trillion kilometers.

**Terms Relating to Motion**

- **rotation** The spinning of an object around its axis. For example, Earth rotates once each day around its axis, which is an imaginary line connecting the North Pole to the South Pole (and passing through the center of Earth).

- **revolution** (or orbit) The orbital motion of one object around another. For example, Earth revolves (orbits) around the Sun once each year.

- **expansion (of the universe)** We say that the universe is expanding because the average distance between galaxies is increasing with time. Note that while the universe as a whole is expanding, individual galaxies and their contents (as well as groups and clusters of galaxies) are not expanding.

On a very large scale, the universe appears frothlike, with galaxies and galaxy clusters loosely arranged in giant chains and sheets. The galaxies and galaxy clusters are more tightly packed in some places than in others, forming giant structures called **superclusters.** The supercluster to which our Local Group belongs is called, not surprisingly, the Local **Supercluster.** Between the vast groupings of galaxies lie huge voids containing few, if any, galaxies.
Finally, the universe is the sum total of all matter and energy, encompassing the superclusters and voids and everything within them. To review the different levels of structure in the universe, you might imagine how a faraway friend would address a postcard to Earth (Figure 1.2).

Think About It
Some people think that our tiny physical size in the vast universe makes us insignificant. Others think that our ability to learn about the wonders of the universe gives us significance despite our small size. What do you think?

Our Cosmic Origins
How did we come to be? Much of the rest of this text discusses the scientific evidence concerning our cosmic origins, and we'll see that humans are newcomers in an old universe. For now, let's look at a quick overview of the scientific story of creation, as summarized in Figure 1.3.

Figure 1.3
Our cosmic origins: All the matter and energy in the universe was created in the Big Bang. This sequence of paintings shows the progression of that matter and energy from the Big Bang to human life. Note that the elements from which we are made were produced in stars that shined long ago. These elements formed Earth through the recycling role played by our galaxy.

As we'll discuss shortly, telescopic observations of distant galaxies show that the entire universe is expanding. That is, average distances between galaxies are increasing with time. If the universe is expanding, everything must have been closer together in the past. From the observed rate of expansion, astronomers estimate that the expansion started about 14 billion years ago. Astronomers call this beginning the Big Bang.

Expansion Versus Gravity
The universe as a whole has continued to expand ever since the Big Bang, but on smaller size scales the force of gravity has drawn matter together. Structures such as galaxies and clusters of galaxies occupy regions where gravity has won out against the overall expansion. That is, while the universe as a whole continues to expand, individual galaxies and their contents do not expand. Most galaxies, including our own Milky Way, probably formed within a few billion years after the Big Bang.

Within galaxies, gravity drives the collapse of clouds of gas and dust to form stars and planets. Stars are not living organisms, but they nonetheless go through “life cycles.” After their birth in giant clouds of gas and dust, stars shine for millions or billions of years. The energy that makes stars shine comes from nuclear fusion, the process in which lightweight atomic nuclei smash together and stick (or fuse) to make heavier nuclei. Nuclear fusion occurs deep in a star’s core throughout its life. A star “dies” when it finally exhausts all its usable fuel for fusion.
In its final death throes, a star blows much of its content back out into space. In particular, massive (but short-lived) stars die in titanic explosions called supernovae. The returned matter mixes with other matter floating between the stars in the galaxy, eventually becoming part of new clouds of gas and dust from which new generations of stars can be born. Thus, galaxies function as cosmic recycling plants, recycling material expelled from dying stars into new generations of stars and planets. Our own solar system is a product of many generations of such recycling.

Star Stuff
The recycling of stellar material has another, even more important, connection to our own existence. By studying stars of different ages, we have learned that the early universe contained only the simplest chemical elements: hydrogen and helium (and a trace amount of lithium). We and Earth are made primarily of “other” elements, such as carbon, nitrogen, oxygen, and iron. Where did these other elements come from? Astronomers have discovered that all these elements were manufactured by massive stars, either through the nuclear fusion that makes them shine or through nuclear reactions accompanying the explosions that end their lives.

The processes of heavy-element production and cosmic recycling had already been taking place for several billion years by the time our solar system formed, about 4.6 billion years ago. The cloud that gave birth to our solar system was about 98% hydrogen and helium. The other 2% contained all the other chemical elements. The small rocky planets of our solar system, including Earth, were made from a small part of this 2%. We do not know exactly how the elements on the Earth's surface developed into the first forms of life, but it appears that microbial life was already flourishing on Earth more than 3.5 billion years ago. Biological evolution took over once life arose, leading to the great diversity of life on Earth today.

In summary, most of the material from which we and our planet are made was created inside stars that died before the birth of our Sun. We are intimately connected to the stars because we are products of stars. In the words of astronomer Carl Sagan (1934–1996), we are “star stuff.”

Seeing into the Past
We study the universe by studying light from distant stars and galaxies. Light travels extremely fast by earthly standards: The speed of light is 300,000 kilometers per second. At this speed it would be possible to circle Earth nearly eight times in just 1 second. Nevertheless, even light takes a substantial amount of time to travel the vast distances in space.

For example, light takes about 1 second to reach Earth from the Moon and about 8 minutes to reach Earth from the Sun. Light from the stars takes many years to reach us, so we measure distances to the stars in units called light-years. One light-year is the distance that light can travel in 1 year—about 10 trillion kilometers, or 6 trillion miles. Note that a light-year is a unit of distance, not time.

The brightest star in the night sky, Sirius, is about 8 light-years from our solar system. This means it takes light from Sirius about 8 years to reach us. Thus, when we look at Sirius, we see light that left the star about 8 years ago.
The Orion Nebula, a star-forming region visible to the naked eye as a small, cloudy patch in the sword of the constellation Orion, lies about 1,500 light-years from Earth (Figure 1.4). Thus, we see the Orion Nebula as it looked about 1,500 years ago—about the time of the fall of the Roman Empire. If any major events have occurred in the Orion Nebula since that time, we cannot yet know about them because the light from these events would not yet have reached us.

Figure 1.4
The Orion Nebula (a) is a giant cloud of gas and dust in which new stars and planets are forming. It is located about 1,500 light-years from Earth, which means the light recorded in the photograph took about 1,500 years to reach us. Thus, we see it as it was about 1,500 years ago. Photograph (b) shows the constellation Orion, with labels for several bright stars and the location of the Orion Nebula. The Orion Nebula is faintly visible to the naked eye, and you can see some detail with a good pair of binoculars. (Note: All stars are so far away that they appear as pinpoints of light. Brighter stars appear larger in the photograph only because they are overexposed. The crosses on the bright stars are an artifact of the telescope used to take the photograph.)

Because light takes time to travel through space, we are led to a remarkable fact:

The farther away we look in distance, the further back we look in time.

This fact allows us to see what parts of the universe looked like in the distant past. For example, if we look at a galaxy that is 1 billion light-years away, its light has taken 1 billion years to reach us—which means we are seeing it as it looked 1 billion years ago. (*footnote)

Now assume the universe is 14 billion years old. In that case, if we look at a galaxy that is 7 billion light-years away, its light has taken 7 billion years to reach us—which means we are seeing it as it looked 7 billion years ago, when the universe was only half its current age. If we look at a galaxy that is 12 billion light-years away, we see it as it was 12 billion years ago, when the universe was only 2 billion years old. Thus, simply by looking to great distances, we can see what parts of the universe looked like when the universe was younger. The key limitation to this ability is the power of our telescopes. Modern telescopes are capable of seeing bright galaxies 12 billion or more light-years away, and astronomers eagerly await new telescopes that will allow us to see fainter objects at such great distances.

Because looking to great distances means looking into the past, the age of the universe imposes a fundamental limit on how far we can see (Figure 1.5). If the universe is 14 billion years old, we cannot possibly see anything more than 14 billion light-years away, because we'd be trying to look to a time before the universe existed. Thus, our observable universe—the portion of the entire universe that we can potentially observe—consists only of objects that lie within 14 billion light-years of Earth. This fact does not put any limit on the size of the entire universe.
universe, which may be far larger than our observable universe. We simply have no hope of seeing or studying anything beyond the bounds of our observable universe.

Figure 1.5
Figure 1.5 Because light travels at a finite speed, looking farther away in space means looking further back in time. Thus, the age of the universe limits the extent of our observable universe. This figure assumes the universe is 14 billion years old.

It is amazing to realize that any “snapshot” of a distant galaxy or cluster of galaxies is a picture of both space and time. For example, the Great Galaxy in Andromeda, also known as M31, lies about 2.5 million light-years from Earth. Figure 1.6 is therefore a picture of how M31 looked about 2.5 million years ago, when early humans were first walking on Earth. Moreover, the diameter of M31 is about 100,000 light-years, so light from the far side of the galaxy requires 100,000 years more to reach us than light from the near side. Thus, the picture of M31 shows 100,000 years of time. This single photograph captured light that left the near side of the galaxy some 100,000 years later than the light it captured from the far side. When we study the universe, it is impossible to separate space and time.

Figure 1.6
Figure 1.6 M31, the Great Galaxy in Andromeda, is about 2.5 million light-years away, so this photo captures light that traveled through space for 2.5 million years to reach us. Because the galaxy is 100,000 light-years in diameter, the photo also captures 100,000 years of time in M31. We see the galaxy's near side as it looked 100,000 years later than the time at which we see the far side.

Think About It
Suppose that, at this very moment, students are studying astronomy on planets somewhere in the Great Galaxy in Andromeda. What would they see as they look from afar at our Milky Way? Could they know that we exist here on Earth? Explain.

Mathematical Insight
How Far Is a Light-Year?
It's easy to calculate the distance represented by a light-year if you remember that

\[ \text{distance} = \text{speed} \times \text{time} \]

For example, if you travel at a speed of 50 kilometers per hour for 2 hours, you will travel 100 kilometers. A light-year is the distance covered by light, traveling at a speed of 300,000 kilometers per second, in a time of 1 year. In the process of multiplying the speed and the time, you must convert the year to seconds in order to arrive at a final answer in units of kilometers.
Thus, “1 light-year” is just an easy way of saying “9.46 trillion kilometers” or “almost 10 trillion kilometers.”

Common Misconceptions
The Meaning of a Light-Year
A recent advertisement illustrated a common misconception by claiming “It will be light-years before anyone builds a better product.” This advertisement makes no sense, because a light-year is a unit of distance, not a unit of time. If you are unsure whether the term light-years is being used correctly, try testing the statement by remembering that 1 light-year is approximately 10 trillion kilometers, or 6 trillion miles. The advertisement then reads “It will be 6 trillion miles before anyone builds a better product,” which clearly does not make sense.

The Incredible Distances to the Stars
Imagine that you start at the Voyage model Sun in Washington, D.C., as pictured in Figure 1.8b. You walk the roughly 600-meter distance to Pluto (just over ½ mile) and then decide to keep going to find the nearest star besides the Sun. How far would you have to go?

<table>
<thead>
<tr>
<th>Object</th>
<th>Real Diameter (km)</th>
<th>Real Distance from Sun (average)</th>
<th>Model Diameter (mm)</th>
<th>Model Distance from Sun (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>1,392,500</td>
<td>–</td>
<td>139 mm = 13.9 cm</td>
<td>–</td>
</tr>
<tr>
<td>Mercury</td>
<td>4,880</td>
<td>57.9 million km</td>
<td>0.5 mm</td>
<td>6 m</td>
</tr>
<tr>
<td>Venus</td>
<td>12,100</td>
<td>108.2 million km</td>
<td>1.2 mm</td>
<td>11 m</td>
</tr>
<tr>
<td>Earth</td>
<td>12,760</td>
<td>149.6 million km</td>
<td>1.3 mm</td>
<td>15 m</td>
</tr>
<tr>
<td>Mars</td>
<td>6,790</td>
<td>227.9 million km</td>
<td>0.7 mm</td>
<td>23 m</td>
</tr>
<tr>
<td>Jupiter</td>
<td>143,000</td>
<td>778.3 million km</td>
<td>14.3 mm</td>
<td>78 m</td>
</tr>
<tr>
<td>Saturn</td>
<td>120,000</td>
<td>1,427 million km</td>
<td>12.0 mm</td>
<td>143 m</td>
</tr>
<tr>
<td>Uranus</td>
<td>52,000</td>
<td>2,870 million km</td>
<td>5.2 mm</td>
<td>287 m</td>
</tr>
<tr>
<td>Neptune</td>
<td>48,400</td>
<td>4,497 million km</td>
<td>4.8 mm</td>
<td>450 m</td>
</tr>
<tr>
<td>Pluto</td>
<td>2,260</td>
<td>5,900 million km</td>
<td>0.2 mm</td>
<td>590 m</td>
</tr>
</tbody>
</table>

Amazingly, you would need to walk to California. That is, on the same scale that allows you to walk from the Sun to Pluto in minutes, even the nearest stars would be more than 4,000
kilometers (2,500 miles) away. If this answer seems hard to believe, you can calculate it for yourself. A light-year is about 10 trillion kilometers, which becomes 1,000 kilometers on the 1-to-10-billion scale (10 trillion ÷ 10 billion = 1,000). The nearest star system to our own, called Alpha Centauri (Figure 1.10), is about 4.4 light-years away. Thus, Alpha Centauri's real distance of about 4.4 light-years becomes about 4,400 kilometers (2,700 miles) on the 1-to-10-billion scale, or roughly equivalent to the distance across the United States. (Alpha Centauri is actually a three-star system, which sometimes leads to confusion about the identity of the “nearest star.” Proxima Centauri, the smallest and dimmest of the three stars, is over 0.1 light-year closer to us than the other two stars. Thus, while Alpha Centauri is the nearest star system to our own, Proxima Centauri is the nearest individual star.)

Figure 1.10
This photograph and diagram show the constellation Centaurus, which is visible only from tropical and southern latitudes. Note the location of Alpha Centauri, the nearest star system to our own. Its real distance is about 4.4 light-years, which is about 4,400 kilometers (2,700 miles) on the 1-to-10-billion Voyage scale. In other words, on the same scale on which Pluto is a short walk away, the distance to the nearest stars is equivalent to the distance across the United States.

The tremendous distances to the stars give us some perspective on the technological challenge of astronomy. For example, because the largest star of the Alpha Centauri system is roughly the same size and brightness as our Sun, viewing it in the night sky is somewhat like being in Washington, D.C., and seeing a very bright grapefruit in San Francisco (neglecting the problems introduced by the curvature of the Earth). It may seem remarkable that we can see this star at all, but the blackness of the night sky allows the naked eye to see it as a faint dot of light. It looks much brighter through powerful telescopes, but we still cannot see any features of the star's surface.

Now, consider the difficulty of seeing planets orbiting nearby stars. It is equivalent to looking from Washington, D.C., and trying to see ball points or marbles orbiting grapefruits in California (or beyond). You probably won't be surprised to learn that we have not yet seen such planets directly. Indeed, the bigger surprise may be that we have discovered more than 100 extrasolar planets (planets around other stars) through indirect techniques. These techniques involve searching for signs that a planet is affecting the motion or the light of the star it orbits [Section 9.6]. All of the extrasolar planets detected as of 2003 are closer in size to Jupiter than to Earth. However, with planet-detecting technology improving rapidly, astronomers are hopeful that the first discoveries of Earth-size planets around other stars will occur within a decade.

Our examination of stellar distances also offers a sobering lesson about the possibility of travel to the stars. Although science fiction shows like Star Trek and Star Wars may make interstellar travel seem easy, the reality is far different. Consider the Voyager 2 spacecraft. Launched in 1977, Voyager 2 flew by Jupiter in 1979, Saturn in 1981, Uranus in 1986, and Neptune in 1989. (Its trajectory did not take it near Pluto.) Voyager 2 is now bound for the stars at a speed of close to 50,000 kilometers per hour—about 100 times as fast as a speeding bullet. Even at this speed, Voyager 2 would take about 100,000 years to reach Alpha Centauri if it were headed in that direction (which it's not). Convenient interstellar
travel remains well beyond our present technology [Section 24.5].

The Scale of the Milky Way Galaxy

The vast separation between our solar system and Alpha Centauri is typical of the separations among star systems here in the outskirts of the Milky Way Galaxy. Thus, the 1-to-10-billion scale is useless for modeling even just a few dozen of the nearest stars, because they could not all be spaced properly on the Earth's surface. Visualizing the entire galaxy requires a new scale.

Let's further reduce our solar system scale by a factor of 1 billion (making it a scale of 1 to 1019). On this new scale, each light-year becomes 1 millimeter, and the 100,000-light-year diameter of the Milky Way Galaxy becomes 100 meters, or about the length of a football field. Visualize a football field with a scale model of our galaxy centered over midfield. Our entire solar system is a microscopic dot located around the 20-yard line. The 4.4-light-year separation between our solar system and Alpha Centauri becomes just 4.4 millimeters on this scale—smaller than the width of your little finger. If you stood at the position of our solar system in this model, millions of star systems would lie within reach of your arms.

Common Misconceptions

Confusing Very Different Things

Most people are familiar with the terms solar system and galaxy, but people sometimes mix them up. Notice how incredibly different our solar system is from our galaxy. Our solar system is a single star system consisting of our Sun and the various objects that orbit it, including Earth and eight other planets. Our galaxy is a collection of some 100 billion star systems—so many that it would take thousands of years just to count them. Thus, confusing the terms solar system and galaxy represents a mistake by a factor of 100 billion—a fairly big mistake!

Another way to put the galaxy into perspective is to consider its number of stars—more than 100 billion. Imagine that tonight you are having difficulty falling asleep (perhaps because you are contemplating the scale of the universe). Instead of counting sheep, you decide to count stars. If you are able to count about one star each second, on average, how long would it take you to count 100 billion stars in the Milky Way? Clearly, the answer is 100 billion (1011) seconds, but how long is that? Amazingly, 100 billion seconds turns out to be more than 3,000 years. (You can confirm this by dividing 100 billion by the number of seconds in 1 year.) Thus, you would need thousands of years just to count the stars in the Milky Way Galaxy, and this assumes you never take a break—no sleeping, no eating, and absolutely no dying!
The Number of Stars in the Universe

As incredible as the scale of our galaxy may seem, the Milky Way is only one of at least 100 billion galaxies in the observable universe. Just as it would take thousands of years to count the stars in the Milky Way, it would take thousands of years to count all the galaxies. Think for a moment about the total number of stars in all these galaxies. If we assume 100 billion stars per galaxy, the total number of stars in the observable universe is roughly $100 \times 100$ billion or $10,000,000,000,000,000,000,000$ ($10^{22}$).

How big is this number? Visit a beach. Run your hands through the fine-grained sand. Imagine counting each tiny grain of sand as it slips through your fingers. Then imagine counting every grain of sand on the beach and continuing on to count every grain of dry sand on every beach on Earth. If you could actually complete this task, you would find that the number of grains of sand is similar to the number of stars in the observable universe (Figure 1.11).

Think About It

Contemplate the fact that there may be as many stars in the observable universe as grains of sand on all the beaches on Earth and that each star is a potential sun for a system of planets. With so many possible homes for life, do you think it is conceivable that life exists only on Earth? Why or why not?
The Scale of the Milky Way Galaxy

The vast separation between our solar system and Alpha Centauri is typical of the separations among star systems here in the outskirts of the Milky Way Galaxy. Thus, the 1-to-10-billion scale is useless for modeling even just a few dozen of the nearest stars, because they could not all be spaced properly on the Earth's surface. Visualizing the entire galaxy requires a new scale.

Let's further reduce our solar system scale by a factor of 1 billion (making it a scale of 1 to 1019). On this new scale, each light-year becomes 1 millimeter, and the 100,000-light-year diameter of the Milky Way Galaxy becomes 100 meters, or about the length of a football field. Visualize a football field with a scale model of our galaxy centered over midfield. Our entire solar system is a microscopic dot located around the 20-yard line. The 4.4-light-year separation between our solar system and Alpha Centauri becomes just 4.4 millimeters on this scale—smaller than the width of your little finger. If you stood at the position of our solar system in this model, millions of star systems would lie within reach of your arms.

Common Misconceptions

Confusing Very Different Things

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The Scale of Time

Now that we have developed some perspective on the scale of space, we can do the same for the scale of time. Imagine the entire history of the universe, from the Big Bang to the present, compressed into a single year. We can represent this history with a cosmic calendar, on which the Big Bang takes place at the first instant of January 1 and the present day is just before the stroke of midnight on December 31 (Figure 1.12). For a universe that is about 14 billion years old, each month on the cosmic calendar represents a little more than 1 billion years. (More precisely, an average month represents 1.17 billion years.)
The cosmic calendar compresses the history of the universe into 1 year. This version assumes that the universe is 14 billion years old, so each month represents a little more than 1 billion years. Only within the last few seconds of the last day has human civilization taken shape. (This version of the cosmic calendar is adapted from one created by Carl Sagan.)

On this scale, the Milky Way Galaxy probably formed sometime in February. Many generations of stars lived and died in the subsequent cosmic months, enriching the galaxy with the “star stuff” from which we and our planet are made.

Our solar system and our planet did not form until early September on this scale, or 4.6 billion years ago in real time. By late September, life on Earth was flourishing. However, for most of Earth's history, living organisms remained relatively primitive and microscopic in size. On the scale of the cosmic calendar, recognizable animals became prominent only in mid-December, with the period of diverse evolution that biologists call the Cambrian explosion [Section 14.5]. Early dinosaurs appeared on the day after Christmas. Then, in a cosmic instant, the dinosaurs disappeared forever—probably due to the impact of an asteroid or a comet [Section 13.6]. In real time, the death of the dinosaurs occurred some 65 million years ago, but on the cosmic calendar it was only yesterday. With the dinosaurs gone, small furry mammals inherited Earth. Some 60 million years later, or around 9 P.M. on December 31 of the cosmic calendar, early hominids (human ancestors) walked upright.

Perhaps the most astonishing thing about the cosmic calendar is that the entire history of human civilization falls into just the last half-minute. The ancient Egyptians built the pyramids only about 11 seconds ago on this scale. About 1 second ago, Kepler and Galileo proved that Earth orbits the Sun rather than vice versa. The average college student was born about 0.05 second ago, around 11:59:59.95 P.M. on the cosmic calendar. On the scale of cosmic time, the human species is the youngest of infants, and a human lifetime is a mere blink of an eye.

Think About It

Notice that, while life has existed for most of our planet's history, intelligent life is a very recent development. Some people use this fact to argue that even if life itself is common in the universe, intelligent life and civilizations will prove to be very rare. Explain the logic behind this argument. Then try to think of counterarguments to explain why it might still be possible for thousands or millions of civilizations to exist in our galaxy alone. Which arguments do you find most persuasive? Defend your opinion.

Rotation and Orbit

The most basic motions of Earth are its rotation (spin) and its orbit (sometimes called revolution) around the Sun. Earth rotates once each day around its axis, an imaginary line connecting the North Pole to the South Pole (and passing through the center of Earth). Although we do not feel any obvious effects from Earth's rotation, the speed of rotation is substantial (Figure 1.13). Unless you live at very high latitude, you are whirling around Earth's axis at a speed of 1,000 kilometers
per hour (600 miles per hour) or more–faster than most airplanes travel.

Figure 1.13
As Earth rotates, your speed around Earth's axis depends on your latitude. Unless you live at very high latitude, your speed is over 1,000 km/hr. Notice that Earth rotates counterclockwise as viewed from above the North Pole, so you are always rotating from west to east–which is why the Sun rises in the east and sets in the west.

Earth rotates from west to east, which is counterclockwise as viewed from above the North Pole. As a result, the Sun (as well as the Moon and stars) appears to go around us in the opposite direction, from east to west. That is why the Sun rises in the east and sets in the west each day. (We will discuss the apparent motion of the sky in more detail in the next chapter.)

At the same time Earth is rotating, it is also orbiting around the Sun. It takes 1 year to complete each orbit. Again, while we don't feel any effects from the orbit, the speed is quite impressive: We and our planet are right now racing around the Sun at a speed in excess of 100,000 kilometers per hour (60,000 miles per hour).

Earth's orbital path defines a flat plane that we call the **ecliptic plane**. Earth's axis happens to be tilted by 231/2° from a line perpendicular to the ecliptic plane (Figure 1.14). Keep in mind that this notion of tilt makes sense only in relation to the ecliptic plane. That is, the idea of “tilt” by itself has no meaning in space, where there is no absolute up or down. In space, “up” and “down” mean only away from the center of Earth (or another planet) and toward the center of Earth, respectively.

Figure 1.14
Earth's axis is tilted 231/2° from a line perpendicular to the ecliptic plane, the plane of Earth's orbit around the Sun. The axis remains pointed in the same direction in space–toward Polaris, the North Star–at all times throughout the year. From far above the North Pole, you would notice that Earth rotates and orbits counterclockwise.

Think About It
If there is no up or down in space, why do you think nearly all globes have the North Pole on top and the South Pole on the bottom? Would it be equally correct to have the South Pole on top or to turn the globe sideways? Explain.

Earth's rotation and orbit exhibit many other features, some that are easy to notice and others that are quite subtle. For our purposes in this book, three other key features are important to understand and will come up in later discussions.

Earth's axis remains pointed in the same direction in space at all times throughout each year. We'll see in Chapter 2 how this fact helps explain the seasons. The axis (going from south to north) happens to point very nearly in the direction of a star called Polaris, which is why Polaris is also known as the North Star.

Earth orbits the Sun in the same direction that it rotates on its axis. That is, both
rotation and orbit go counterclockwise as viewed from above the North Pole. This is not a coincidence but a consequence of how our planet was born. The giant cloud of gas and dust from which our solar system was born must also have been spinning [Section 9.2], and the direction of the cloud's spin is reflected in the directions of Earth's rotation and orbit.

Earth's orbit is not a perfect circle. Rather, it is a slightly oval shape known as an ellipse [Section 3.4]. As a result, Earth's distance from the Sun varies slightly over the course of each year (Figure 1.15). The Earth's average distance from the Sun, which is about 150 million kilometers (93 million miles), is given a special name: an astronomical unit, or AU. (More technically, 1 AU is the semimajor axis of the Earth's elliptical orbit.) Distances within our solar system are commonly described in astronomical units because these are easier to interpret than units in kilometers. For example, knowing that Mars is about 230 million kilometers from the Sun may not mean much to you, but knowing that it is 1.5 AU from the Sun immediately tells you that Mars is 1.5 times as far from the Sun as is Earth.

Traveling in the Milky Way Galaxy
Rotation and orbit are only a small part of the travels of spaceship Earth. In fact, our entire solar system is on a great journey within the Milky Way Galaxy.

Our Local Solar Neighborhood
Let's begin with the motion of our solar system relative to nearby stars in what we call our local solar neighborhood (the region of the Sun and nearby stars). Figure 1.16 shows that stars within the local solar neighborhood move essentially at random relative to one another. It also offers an important reminder of the incredible scale of the galaxy. Imagine drawing the tiniest dot that you can make on the galaxy painting in Figure 1.16. Your dot will probably be about 10,000 times smaller than the picture of the galaxy as a whole—but it will cover a region representing more than 10 million stars! (The entire galaxy contains more than 100 billion stars, and 100 billion ÷ 10,000 = 10 million.) We usually think of our local solar neighborhood as an even smaller region of the galaxy including the nearest few thousand to few million stars.

The stars of the local solar neighborhood (or any other small region of the galaxy) generally move quite fast relative to one another. For example, we are moving relative to nearby stars at an average speed of about 70,000 kilometers per hour (40,000 miles per hour), about three times as fast as the Space Station orbits Earth. Given these high speeds, why don't we see nearby stars racing around our
sky?

The answer lies in their vast distances from us. You've probably noticed that a distant airplane appears to move through your sky more slowly than one flying close overhead. If we extend this idea to the stars, we find that even at speeds of 70,000 kilometers per hour stellar motions would be noticeable to the naked eye only if we watched them for thousands of years. That is why the patterns in the constellations seem to remain fixed. Nevertheless, in 10,000 years the constellations will be noticeably different from those we see today. In 500,000 years they will be unrecognizable. If you could watch a time-lapse movie made over millions of years, you would see stars racing across our sky.

Think About It

Despite the chaos of motion in the local solar neighborhood over millions and billions of years, collisions between star systems are extremely rare. Explain why. (Hint: Consider the sizes of star systems, such as the solar system, relative to the distances between them.)

Galactic Rotation

If you look closely at leaves floating in a stream, their motions relative to one another might appear random, just like the motions of stars in the local solar neighborhood. As you widen your view, you see that all the leaves are being carried in the same general direction by the downstream current. In the same way, as we widen our view beyond the local solar neighborhood the seemingly random motions of its stars give way to a simpler and even faster motion: The entire Milky Way Galaxy is rotating.

Stars at different distances from the galactic center take different amounts of time to complete an orbit. Our solar system, located about 28,000 light-years from the galactic center, completes one orbit of the galaxy in about 230 million years (Figure 1.17). Even if you could watch from outside our galaxy, this motion would be unnoticeable to your naked eye. However, if you calculate the speed of our solar system as we orbit the center of the galaxy, you will find that it is close to 800,000 kilometers per hour (500,000 miles per hour).

The galaxy's rotation reveals one of the greatest mysteries in science—one that we will study in depth in Chapter 22. The speeds at which stars orbit the galactic center depend on the strength of gravity, and the strength of gravity depends on how mass is distributed throughout the galaxy. Thus, careful study of the galaxy's rotation allows us to determine the distribution of mass in the galaxy.

Such studies suggest that the stars in the disk of the galaxy represent only the “tip of the iceberg” compared to the mass of the entire galaxy (Figure 1.18). That is, most of the mass of the galaxy seems to be located outside the visible disk, in what we call the galaxy's halo. We don't know the nature of this mass. Because we have not detected any light coming from it, we call it dark matter. Studies of other galaxies suggest that they also are made mostly of dark matter. In fact, most of the mass in the universe seems to be made of this mysterious dark matter, but we do not yet know what it is.
The billions of galaxies in the universe also move relative to one another. Within the Local Group (see Figure 1.1), some of the galaxies move toward the Milky Way Galaxy, some move away from it, and some move in more complex ways. For example, two small galaxies, known as the Large and Small Magellanic Clouds, apparently orbit the Milky Way. Again, the speeds are enormous by earthly standards. In fact, the Milky Way is moving toward the Great Galaxy in Andromeda (M 31) at about 300,000 kilometers per hour (180,000 miles per hour)–but this motion is unnoticeable to our eyes. Despite the high speed, we needn't worry about a collision anytime soon. Even if the Milky Way and Andromeda Galaxies are approaching each other head-on (which they might not be), it will be nearly 10 billion years before any collision begins.

When we look outside the Local Group, however, we find two astonishing facts that were first recognized in the 1920s by Edwin Hubble, for whom the Hubble Space Telescope was named:

1. Virtually every galaxy outside the Local Group is moving away from us.
2. The more distant the galaxy, the faster it appears to be racing away from us.

Upon first hearing of these two facts, you might be tempted to conclude that our Local Group (which is held together by gravity) suffers a cosmic case of chicken pox. However, there is a natural explanation: The entire universe is expanding. We'll save details about this expansion for later in the book (Chapter 20), but you can understand the basic idea by thinking about a raisin cake baking in an oven.

Imagine that you make a raisin cake in which the distance between adjacent raisins is 1 centimeter. You place the cake in the oven, where it expands as it bakes. After 1 hour, you remove the cake, which has expanded so that the distance between adjacent raisins has increased to 3 centimeters (Figure 1.19). The expansion of the cake seems fairly obvious. But what would you see if you lived in the cake, as we live in the universe?

![Figure 1.19](image)

Figure 1.19

Figure 1.19 An expanding raisin cake illustrates basic principles of the expansion of the universe. From the outside, the raisin cake appears to expand uniformly. From the inside, anyone living in one of the raisins would find that all other raisins are moving away as the cake expands, with more distant raisins moving away faster. This analogy shows why the fact that more distant galaxies move away from us faster than nearer ones implies that our universe is expanding.

Pick any raisin (it doesn't matter which one), call it the Local Raisin, and identify it in the pictures of the cake both before and after baking. Figure 1.19 shows one possible choice for the Local Raisin, with three nearby raisins labeled. The accompanying table summarizes what you would see if you lived within the Local Raisin. Notice, for example, that Raisin 1 starts out at a distance of 1 centimeter before baking and ends up at a distance of 3 centimeters after baking, which means it moves a distance of 2 centimeters away from the Local Raisin during the hour of baking. Hence, its speed as seen from the Local Raisin is 2 centimeters per hour. Raisin 2 moves from a distance of 2 centimeters before baking to a distance of 6 centimeters after baking, which means it moves a distance of 4 centimeters...
away from the Local Raisin during the hour. Hence, its speed is 4 centimeters per hour, or
twice as fast as the speed of Raisin 1. Generalizing, the fact that the cake is expanding
means that all raisins are moving away from the Local Raisin, with more distant raisins
moving away faster.

Hubble's discovery that galaxies are moving in much the same way as the raisins in the
cake, with most moving away from us and more distant ones moving away faster, implies
that the universe in which we live is expanding much like the raisin cake. If you now imagine
the Local Raisin as representing our Local Group of galaxies and the other raisins as
representing more distant galaxies or clusters of galaxies, you have a basic picture of the
expansion of the universe. Like the expanding dough between the raisins in the cake, space
itself is growing between galaxies. More distant galaxies move away from us faster because
they are carried along with this expansion like the raisins in the expanding cake. And, just as
the raisins themselves do not expand, the individual galaxies and clusters of galaxies do not
expand because they are bound together by gravity.

### Distances and Speeds As Seen from the Local Raisin

<table>
<thead>
<tr>
<th>Raisin Number</th>
<th>Distance Before Baking</th>
<th>Distance After Baking (1 hour later)</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 cm</td>
<td>3 cm</td>
<td>2 cm/hr</td>
</tr>
<tr>
<td>2</td>
<td>2 cm</td>
<td>6 cm</td>
<td>4 cm/hr</td>
</tr>
<tr>
<td>3</td>
<td>3 cm</td>
<td>9 cm</td>
<td>6 cm/hr</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

There's one important distinction between the raisin cake analogy and the universe: Because
a cake is small in size, it has a center and edges that we can see. In contrast, our
observable universe is probably just part of the entire universe, so we could not identify any
center and edges even if the universe had them. The effects of expansion would appear
basically the same from any place in the universe. Anyone living in any galaxy would see
other galaxies moving away, with more distant ones moving faster. No place can claim to
be any more “central” than any other place. Thus, unlike the cake, we say that our universe
has no center.
Summary of Our Motion
Let's summarize the motions we have covered. We spin around Earth's axis as Earth orbits the Sun. Our solar system moves among the stars of the local solar neighborhood as this entire neighborhood orbits the center of the Milky Way Galaxy. Our galaxy, in turn, moves among the other galaxies of the Local Group as the Local Group is carried along with the overall expansion of the universe. Table 1.2 lists the motions and their associated speeds. Spaceship Earth is carrying us on a remarkable journey!

<table>
<thead>
<tr>
<th>Motion</th>
<th>Typical Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotation</td>
<td>1,000 km/hr or more around axis, with one rotation taking 1 day</td>
</tr>
<tr>
<td>orbit of Sun</td>
<td>100,000 km/hr around Sun, with one orbit taking 1 year</td>
</tr>
<tr>
<td>motion within local solar neighborhood</td>
<td>70,000 km/hr relative to nearby stars</td>
</tr>
<tr>
<td>rotation of the Milky Way Galaxy</td>
<td>800,000 km/hr around galactic center, with one galactic rotation taking about 230 million years</td>
</tr>
<tr>
<td>motion within Local Group</td>
<td>300,000 km/hr toward Andromeda Galaxy</td>
</tr>
<tr>
<td>universal expansion</td>
<td>more distant galaxies moving away faster, with the most distant moving at speeds close to the speed of light</td>
</tr>
</tbody>
</table>

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