1

A Modern View of the Universe

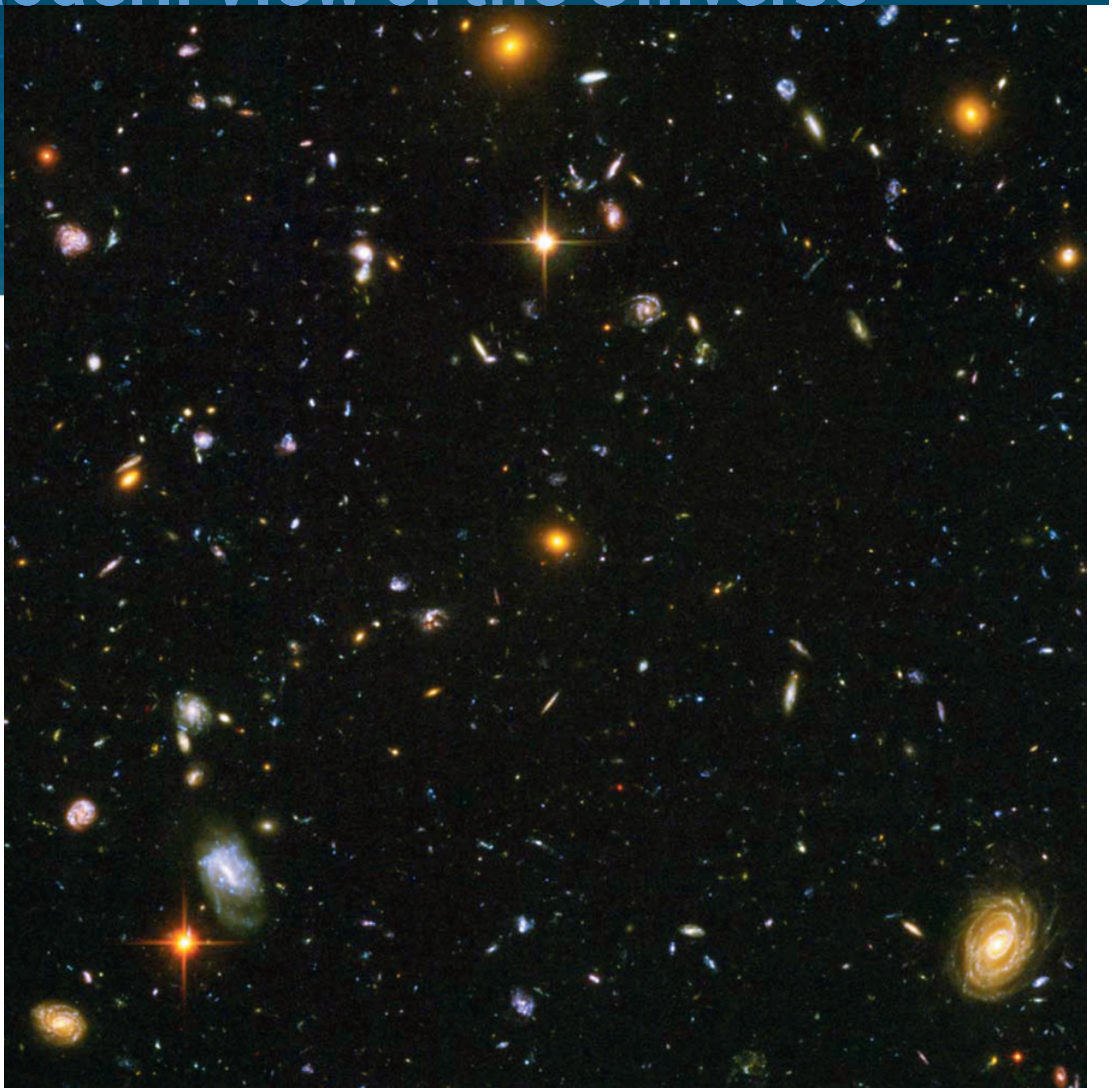
Learning Goals

1.1 Our Place in the Universe
- What is our place in the universe?
- How big is the universe?

1.2 A Brief History of the Universe
- How did we come to be?
- How do our lifetimes compare to the age of the universe?

THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets
- What is a planet?



This Hubble Space Telescope photo shows a piece of the sky so small that you could cover it with a grain of sand at arm's length. Yet it is filled with galaxies, each containing billions of stars much like our Sun, perhaps orbited by their own families of planets. The picture shows more than just the vastness of space, however. It also shows the depths of time: Some of the smaller smudges are galaxies so far away that their light has taken more than 12 billion years to reach us. A major goal of this book is to help you understand what you see in this photograph. We'll begin with a brief survey of our modern, scientific view of the universe.

1.1 Our Place in the Universe

Our ancestors imagined the universe to be relatively small. They placed Earth at the center, surrounded by circles or spheres that carried the Sun, Moon, and planets around us each day. Beyond the planets, they imagined the boundary of the universe to be a sphere filled with stars. These ideas made sense at the time, because they agreed with everyday experience: The Sun, Moon, planets, and stars all *appear* to circle around us each day, and we cannot feel the constant motion of Earth as it rotates on its axis and orbits the Sun. But today we know that these appearances are deceiving, that Earth is *not* the center of the universe, and that our universe is far larger and filled with far greater wonders than our ancestors ever imagined.

What is our place in the universe?

Before we can discuss the universe and its great wonders, we first need to develop a general sense of our place within it. We can do this by thinking about what we might call our "cosmic address," illustrated in **Figure 1.1**.

Earth is a planet in our **solar system,** which consists of the Sun, the planets and their moons, and countless smaller objects that include rocky *asteroids* and icy *comets.* Keep in mind that our Sun is a *star,* just like the stars we see in our night sky.

Our solar system belongs to the 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 is a relatively large galaxy, 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.

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

On a very large scale, observations show that galaxies and galaxy clusters appear to be arranged in giant chains and sheets with huge voids between them; the background of Figure 1.1 shows this large-scale structure. The regions in which galaxies and galaxy clusters are most tightly packed are called **superclusters,** which are essentially clusters of galaxy clusters. Our Local Group is located in the outskirts of the **Local Supercluster.**

Together, all these structures make up our **universe.** In other words, the universe is the sum total of all matter and energy, encompassing the superclusters and voids and everything within them.

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?

Astronomical Distance Measurements Notice that Figure 1.1 is labeled with an approximate size for each structure in kilometers. You can convert from kilometers into miles by multiplying by 0.6 (because 1 kilometer $\approx$ 0.6 mile); for example, 10,000 (10^4) kilometers is about 6000 miles. In astronomy, many distances are so large that kilometers are not the most convenient unit. We will therefore make frequent use of two other distance units:

- One **astronomical unit (AU)** is Earth's average distance from the Sun, which is about 150 million kilometers.
- One **light-year (ly)** is the *distance* that light can travel in 1 year, which is about 10 trillion kilometers. Note that you can find this distance by multiplying the speed of light—300,000 kilometers per second—by the number of seconds in one year (see Tools of Science, p. 9).

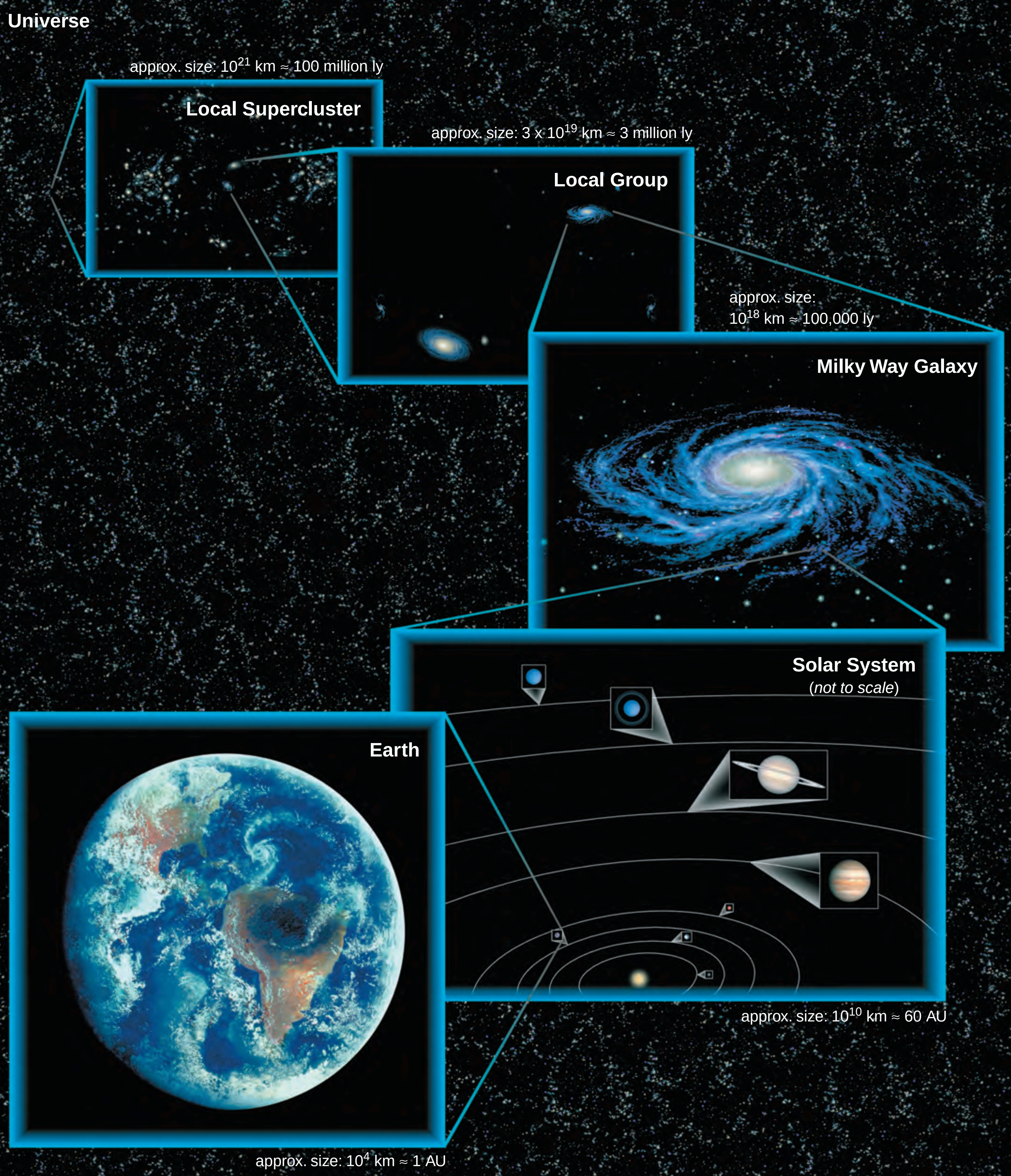
Common Misconceptions

THE MEANING OF A LIGHT-YEAR

You've probably heard people say things like "It will take me light-years to finish this homework!" But a statement like this one doesn't make sense, because light-years are a unit of *distance,* not time. If you are unsure whether the term *light-year* is being used correctly, try testing the statement by using the fact that 1 light-year is about 10 trillion kilometers, or 6 trillion miles. The statement then reads "It will take me 6 trillion miles to finish this homework," which clearly does not make sense.

Figure 1.1

Our Cosmic Address



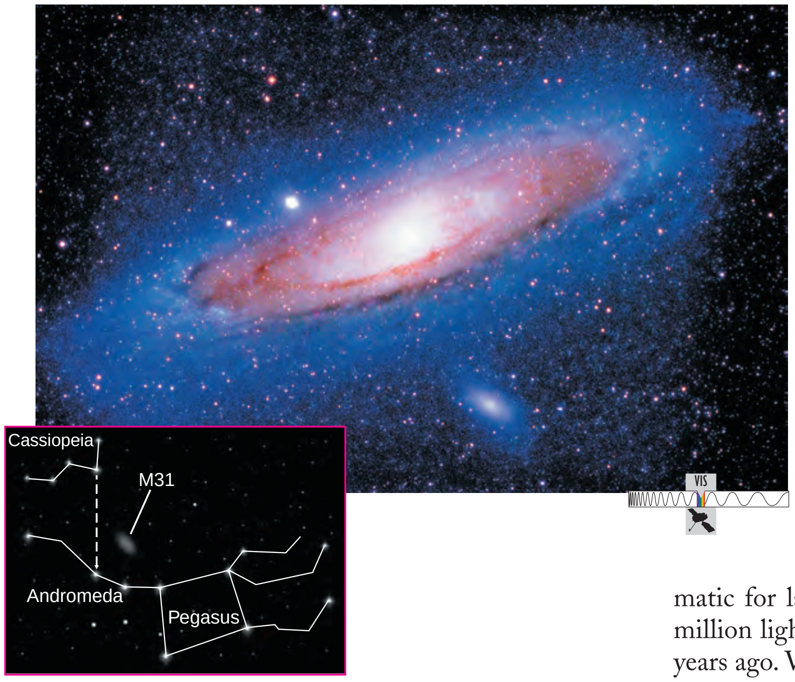


Figure 1.2 | The Andromeda Galaxy (M31). When we look at this galaxy, we see light that traveled through space for 2.5 million years. The inset shows its location in the constellation Andromeda.

Measurements in AU are useful for describing distances in our solar system, while light-years are more useful for describing the distances of stars and galaxies.

Looking Back in Time Light-years are a unit of distance, but they are related to the time it takes light to travel through space. Consider Sirius, the brightest star in the night sky, which is located about 8 light-years away. Because it takes light 8 years to travel this distance, we see Sirius not as it is today, but rather as it was 8 years ago. The star Betelgeuse, a bright red star in the constellation Orion, is 427 light-years away, which means we see it as it was 427 years ago. If Betelgeuse exploded in the past 427 years (a possibility we'll discuss in Chapter 10), we would not yet know it, because the light from the explosion could not yet have reached us.

The general idea that light takes time to travel through space leads to a remarkable fact: **The farther away we look in distance, the further back we look in time.** The effect is dramatic for large distances. The Andromeda Galaxy (**Figure 1.2**) is about 2.5 million light-years away, which means we see it as it looked about 2.5 million years ago. We see more distant galaxies as they were even further in the past.

It's also amazing to realize that any "snapshot" of a distant galaxy is a picture of both space and time. For example, because the Andromeda Galaxy is about 100,000 light-years in diameter, the light we see from the far side of the galaxy must have left on its journey to us some 100,000 years before the light from the near side. Figure 1.2 therefore shows different parts of the galaxy spread over a time period of 100,000 years. When we study the universe, it is impossible to separate space and time.

See it for yourself

You can see the Andromeda Galaxy for yourself, because it is faintly visible to the naked eye. You'll need a dark site and a star chart to find it. When you have this opportunity, remember that you are seeing light that spent 2.5 million years in space before reaching your eyes. If students on a planet in the Andromeda Galaxy were looking at the Milky Way Galaxy, what would they see? Could they know that we exist here on Earth?

The Observable Universe As we'll discuss in Section 1.2, astronomers estimate that the universe is about 14 billion years old. This fact, combined with the fact that looking deep into space means looking far back in time, places a limit on the portion of the universe that we can see, even in principle.

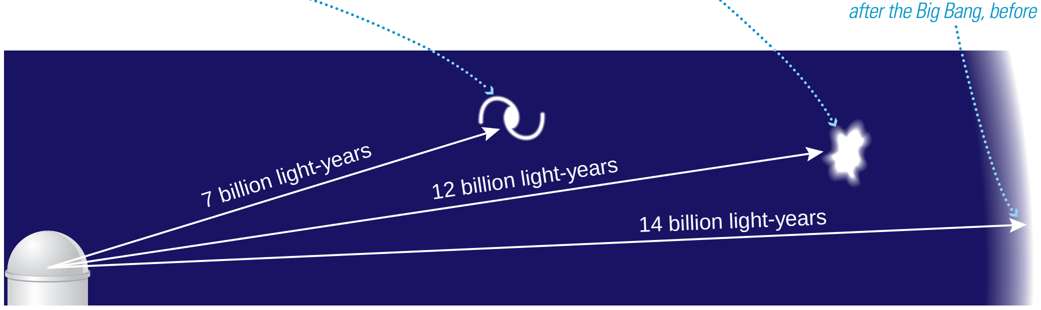
Figure 1.3 shows the idea. If we look at a galaxy that is 7 billion light-years away, we see it as it looked 7 billion years ago—which means we see it as it was when the universe was half its current age. If we look at a galaxy that is 12 billion light-years away—like the most distant ones in the Hubble Space Telescope

Figure 1.3 | The farther away we look in space, the further back we look in time. The age of the universe therefore puts a limit on the size of the *observable* universe—the portion of the entire universe that we could observe in principle.

__Far:__ We see a galaxy 7 billion light-years away as it was 7 billion years ago–when the universe was half its current age of 14 billion years.

__Farther:__ We see a galaxy 12 billion light-years away as it was 12 billion years ago–when the universe was only about 2 billion years old.

__The limit of our observable universe:__ Light from nearly 14 billion light-years away shows the universe as it looked shortly after the Big Bang, before galaxies existed.



__Beyond the observable universe:__ We cannot see anything farther than 14 billion light-years away, because light has not had enough time to reach us.

photo on page 1—we see it as it was 12 billion years ago, when the universe was only 2 billion years old. And if we tried to look beyond 14 billion light-years, we'd be trying to look to a time more than 14 billion years ago—which is before the universe existed. We cannot see anything more than 14 billion light-years away, because light from such distant objects has not yet had time to reach us. This distance of 14 billion light-years therefore marks the boundary of our **observable universe**—the portion of the entire universe that we can potentially observe. Note that this fact does not put any limit on the size of the *entire* 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.

How big is the universe?

Figure 1.1 put numbers on the sizes of different structures in the universe, but these numbers have little meaning for most people—after all, they are literally astronomical. Let's try to put these numbers into perspective.

The Scale of the Solar System Illustrations and photo montages often make our solar system look as if it were crowded with planets and moons, but the reality is far different. One of the best ways to develop perspective on cosmic sizes and distances is to imagine our solar system shrunk down

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Basic Astronomical Objects, Units, and Motions

This box summarizes key definitions used throughout this book.

Basic Astronomical Objects

star A large, glowing ball of gas that generates heat and light through nuclear fusion in its core. Our Sun is a star.

planet A moderately large object that orbits a star and shines primarily by reflecting light from its star. According to a definition adopted in 2006, an object can be considered a planet only if it (1) orbits a star; (2) is large enough for its own gravity to make it round; and (3) has cleared most other objects from its orbital path. An object that meets the first two criteria but not the third, like Pluto, is designated a *dwarf planet.*

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.

comet A relatively small and ice-rich object that orbits a star.

small solar system body An asteroid, comet, or other object that orbits a star but is too small to qualify as a planet or dwarf planet.

Collections of Astronomical Objects

solar system The Sun and all the material that orbits it, including the planets, dwarf planets, and small solar system bodies. Although the term *solar system* technically refers only to our own star system (*solar* means "of the Sun"), it is often applied to other star systems as well.

star system A star (sometimes more than one star) and any planets and other materials that orbit it.

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,* while larger collections are called *clusters.*

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

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

observable universe The portion of the entire universe that can be seen from Earth, at least in principle. 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, such as Earth's daily rotation around the axis. For example, Earth rotates once each day around its axis, which is an imaginary line connecting the North and South Poles.

orbit (revolution) The orbital motion of one object around another due to gravity. For example, Earth orbits around the Sun once each year.

expansion (of the universe) The increase in the average distance between galaxies as time progresses.

Figure 1.4 | This photo shows the pedestals housing the Sun (the gold sphere on the nearest pedestal) and the inner planets in the Voyage scale model solar system (Washington, D.C.). The model planets are encased in the sidewalk-facing disks visible at about eye level on the planet pedestals. The building at the left is the National Air and Space Museum.

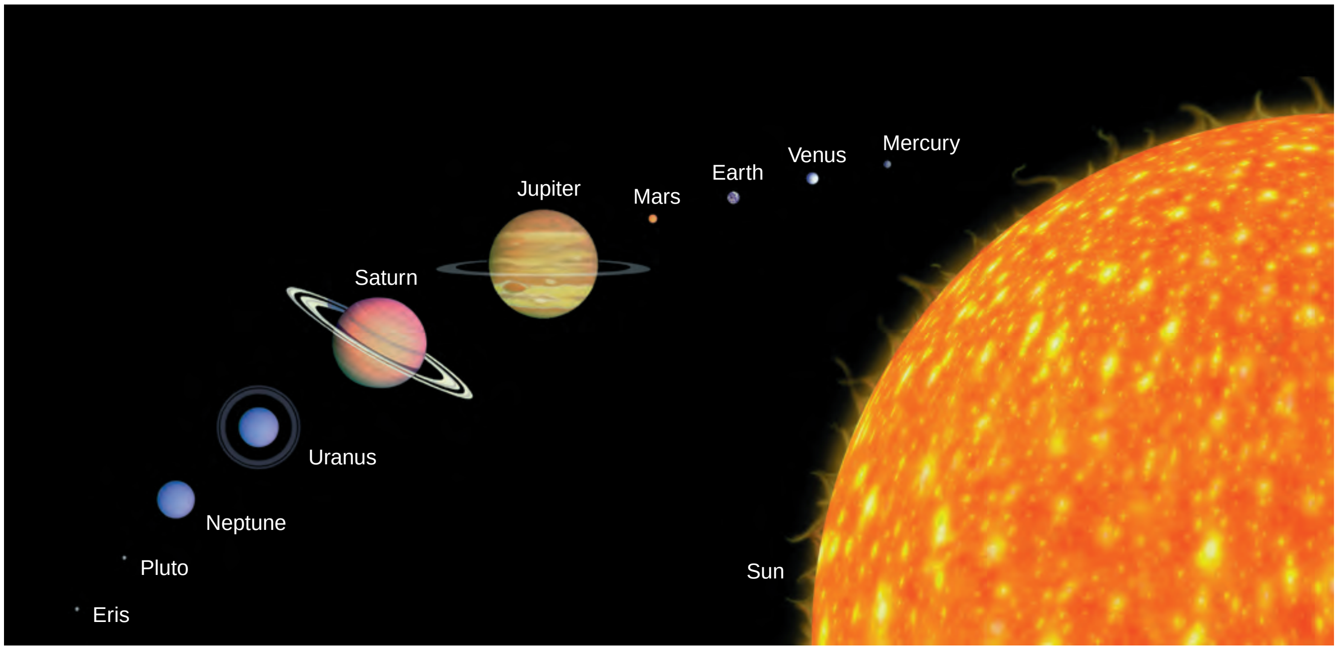
to a scale that would allow you to walk through it. The Voyage scale model solar system in Washington, D.C., makes such a walk possible (**Figure 1.4**). This model shows the Sun and the planets, and the distances between them, at *one ten-billionth* of their actual sizes and distances.

Figure 1.5a shows the Sun and planets at their correct sizes (but not distances) on the Voyage scale: The model Sun is about the size of a large grapefruit, Jupiter is about the size of a marble, and Earth is about the size of the ball point in a pen. You can immediately see some key facts about our solar system. For example, the Sun is far larger than any of the planets; in mass, the Sun outweighs all the planets combined by a factor of more than 1000. The planets also vary considerably in size: The storm on Jupiter known as the Great Red Spot (visible near Jupiter's lower left in the painting) could swallow up the entire Earth.

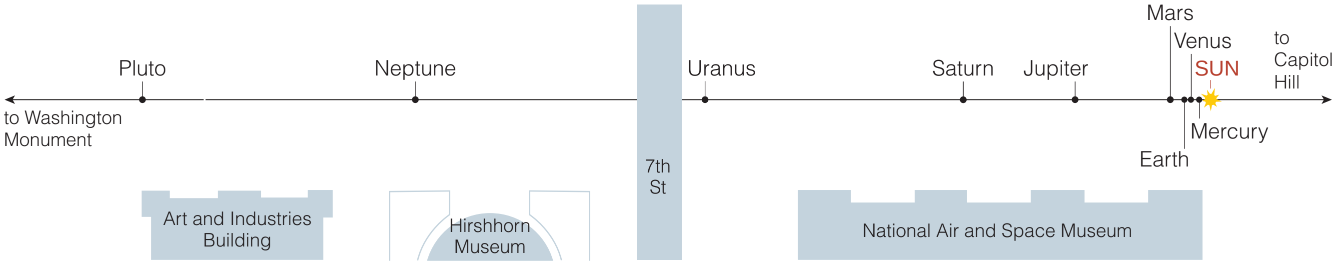
The scale of the solar system is even more remarkable when you combine the sizes shown in Figure 1.5a with the distances illustrated by the map of the Voyage model in **Figure 1.5b.** For example, the ball-point-sized Earth is located about 15 meters (16.5 yards) from the grapefruit-sized Sun, which means you can picture Earth's orbit as a circle of radius 15 meters around a grapefruit.

Perhaps the most striking feature of our solar system when we view it to scale is its emptiness. The Voyage model shows the planets along a straight path, so we'd need to draw each planet's orbit around the model Sun to show the full extent of our planetary system. Fitting all these orbits would require an area measuring more than a kilometer on a side—an area equivalent to more than 300 football fields arranged in a grid. Spread over this large area, only the grapefruit-size Sun, the planets, and a few moons would be big enough to notice with your eyes. The rest of it would look virtually empty (that's why we call it *space*!).

Think about it Earth is the only place in our solar system—and the only place we yet know of in the universe—with conditions suitable for human life. How does visualizing Earth to scale affect your perspective on human existence?



a This painting shows the scaled sizes (but not distances) of the Sun, the planets, and the two largest known dwarf planets.



b This map shows the locations of the Sun and planets in the Voyage model; the distance from the Sun to Pluto is about 600 meters (1/3 mile). Planets are lined up in the model, but in reality each planet orbits the Sun independently and a perfect alignment never occurs.

Figure 1.5 | The Voyage scale model represents the solar system at *one ten-billionth* of its actual size. Pluto is included in the Voyage model, which was built before the International Astronomical Union reclassified Pluto as a dwarf planet.

Seeing our solar system to scale also helps put space exploration into perspective. The Moon, the only other world on which humans have ever stepped (**Figure 1.6**), lies only about 4 centimeters ($1\frac{1}{2}$ inches) from Earth in the Voyage model. On this scale, the palm of your hand can cover the entire region of the universe in which humans have so far traveled. The trip to Mars is more than 150 times as far as the trip to the Moon, even when Mars is on the same side of its orbit as Earth. And while you can walk from the Sun to Pluto in just a few minutes on the Voyage scale, the *New Horizons* spacecraft that is making the real journey will have been in space nearly a decade when it finally flies past Pluto in 2015.

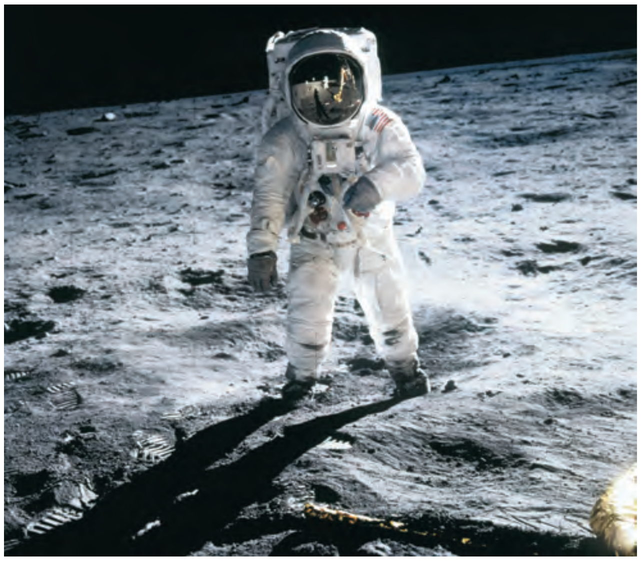


Figure 1.6 | This famous photograph from the first Moon landing (*Apollo 11* in July 1969) shows astronaut Buzz Aldrin, with Neil Armstrong reflected in his visor. Armstrong was the first to step onto the Moon's surface, saying, "That's one small step for a man, one giant leap for mankind."

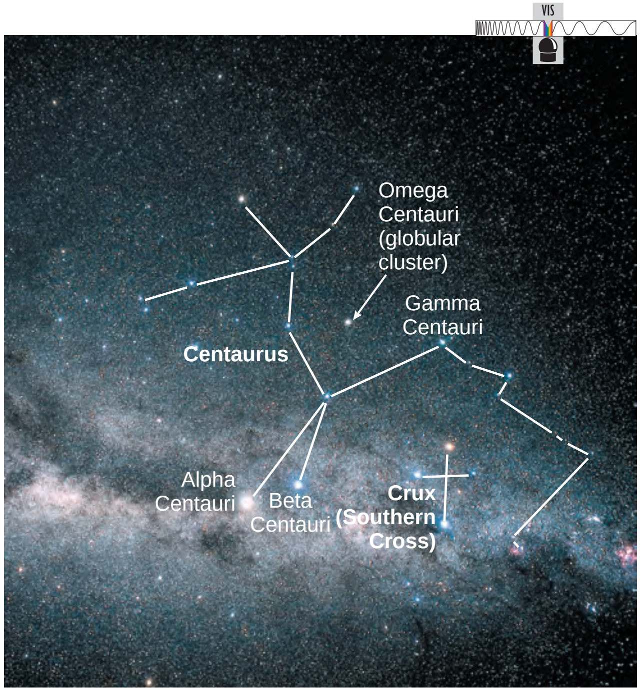


Figure 1.7 | This photograph and diagram show the constellation Centaurus, which is visible from tropical and southern latitudes. Alpha Centauri's real distance is about 4.4 light-years, which is 4400 kilometers on the 1-to-10-billion Voyage scale.

Distance to Stars If you visit the Voyage model in Washington, D.C., you can walk the roughly 600-meter distance from the Sun to Pluto in just a few minutes. But how far would you have to walk to reach the next star on this scale?

Amazingly, you would need to walk to California. If this answer seems hard to believe, you can check it for yourself. A light-year is about 10 trillion kilometers, which becomes 1000 kilometers on the 1-to-10-billion scale (because 10 trillion ÷ 10 billion = 1000). The nearest star system to our own, a three-star system called Alpha Centauri (**Figure 1.7**), is about 4.4 light-years away. That distance is about 4400 kilometers (2700 miles) on the 1-to-10-billion scale, roughly 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 features of the star's surface.

Now, consider the difficulty of detecting *planets* orbiting nearby stars, which is equivalent to looking from Washington, D.C., and trying to find ball points or marbles orbiting grapefruits in California or beyond. When you consider this challenge, it is all the more amazing to realize that we now have technology capable of finding such planets, at least in some cases.

The vast distances to the stars also offer a sobering lesson about interstellar travel. Although science fiction shows like *Star Trek* and *Star Wars* make such travel look 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. It 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. But 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.

The Size of the Milky Way Galaxy We must change our scale to visualize the galaxy, because most stars are so far away that they would not even fit on Earth with the 1-to-10-billion scale we used to visualize the solar system. Let's therefore reduce our scale by another factor of 1 billion (making it a scale of 1 to 10^{19}).

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.

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, how long would it take you to count 100 billion stars in the Milky Way? Clearly, the answer is 100 billion (10^{11}) seconds, but how long is that? Amazingly, 100 billion seconds turns out to be more than 3000 years. (You can confirm this by dividing 100 billion by the number of seconds in 1 year.) 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!

Common Misconceptions

CONFUSING VERY DIFFERENT THINGS

Many people mix up the terms *solar system* and *galaxy,* but they refer to very different things. Our solar system is a single star system, while our galaxy is a vast collection of more than 100 billion star systems. In fact, if you look at the sizes in Figure 1.1, you'll see that our galaxy is about 100 million times larger in diameter than our solar system. So be careful with these terms: Mixing up *solar system* and *galaxy* is a very big mistake!

Stars in the Observable Universe As incredible as the scale of our galaxy may seem, the Milky Way is only one of roughly 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 billion × 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 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 was comparable to the number of stars in the observable universe (**Figure 1.8**).

Figure 1.8 | The number of stars in the observable universe is comparable to the number of grains of dry sand on all the beaches on Earth.

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. How does this affect your view of the possibility that other intelligent civilizations exist?

Tools of Science: Doing the Math

Mathematics is one of the most important tools of science, because it allows scientists to make precise, numerical predictions that can be tested through observations or experiments. These types of tests make it possible for us to gain confidence in scientific ideas. That is why the development of science and mathematics has often gone hand in hand. For example, Sir Isaac Newton developed the mathematics of calculus so that he could do the calculations necessary to test his theory of gravity, and Einstein used new mathematical ideas to work out the details of his general theory of relativity. Fortunately, you don't have to be a Newton or an Einstein to benefit from mathematics in science. Calculations using only multiplication and division can still provide important insights into scientific ideas. Let's look at a few examples.

Example 1: How far is a light-year?

Solution: A light-year (ly) is the distance that light can travel in one year; recall that light travels at the *speed of light,* which is 300,000 km/s. Just as we can find the distance that a car travels in two hours by multiplying the car's speed by two hours, we can find a light-year by multiplying the speed of light by one year. Because we are given the speed of light in kilometers per second, we must carry out the multiplication while converting 1 year into seconds. See Appendix C if you need a review of unit conversions; here, we show the result for this case:

$$\begin{aligned}
1\text{ ly} &= \left(300{,}000\,\frac{\text{km}}{\text{s}}\right) \times (1\text{ yr}) \\
&= \left(300{,}000\,\frac{\text{km}}{\cancel{\text{s}}}\right) \times \left(1\,\cancel{\text{yr}} \times 365\,\frac{\cancel{\text{day}}}{\cancel{\text{yr}}} \times 24\,\frac{\cancel{\text{hr}}}{\cancel{\text{day}}} \times 60\,\frac{\cancel{\text{min}}}{\cancel{\text{hr}}} \times 60\,\frac{\cancel{\text{s}}}{\cancel{\text{min}}}\right) \\
&= 9{,}460{,}000{,}000{,}000\text{ km}
\end{aligned}$$

That is, 1 light-year is equivalent to 9.46 trillion kilometers, which is easier to remember as almost 10 trillion kilometers.

Example 2: How big is the Sun on the 1-to-10-billion scale?

Solution: The Sun's actual radius is 695,000 km, which we express in scientific notation as 6.95×10^5 km. (See Appendix C if you need to review powers of 10 and scientific notation.) To find the Sun's radius on the 1-to-10-billion scale, we divide this actual radius by 10 billion, or 10^{10}:

$$\begin{aligned}
\text{scaled radius} &= \frac{\text{actual radius}}{10^{10}} \\
&= \frac{6.95 \times 10^5\text{ km}}{10^{10}} \\
&= 6.95 \times 10^{(5-10)}\text{ km} \\
&= 6.95 \times 10^{-5}\text{ km}
\end{aligned}$$

This answer is easier to interpret if we convert it to centimeters, which we can do by recalling that there are 1000 (= 10^3) meters in a kilometer and 100 (= 10^2) centimeters in a meter:

$$6.95 \times 10^{-5}\,\cancel{\text{km}} \times \frac{10^3\,\cancel{\text{m}}}{1\,\cancel{\text{km}}} \times \frac{10^2\text{ cm}}{1\,\cancel{\text{m}}} = 6.95\text{ cm}$$

On the 1-to-10-billion scale, the Sun is just under 7 centimeters in radius, or 14 centimeters in diameter.

Example 3: How fast is Earth orbiting the Sun?

Solution: Earth completes one orbit in one year, so we can find its average orbital speed by dividing the circumference of its orbit by one year. Earth's orbit is nearly circular with radius of 1 AU (= 1.5×10^8 km); the circumference of a circle is given by the formula $2\pi \times \text{radius}$. If we want the speed to come out in units of km/hr, we divide this circumference by 1 year converted to hours, as follows:

$$\begin{aligned}
\text{orbital speed} &= \frac{\text{orbital circumference}}{1\text{ yr}} \\
&= \frac{2 \times \pi \times (1.5 \times 10^8\text{ km})}{1\,\cancel{\text{yr}} \times \dfrac{365\,\cancel{\text{day}}}{\cancel{\text{yr}}} \times \dfrac{24\text{ hr}}{\cancel{\text{day}}}} \\
&\approx 107{,}000\text{ km/hr}
\end{aligned}$$

Earth's average speed as it orbits the Sun is more than 100,000 km/hr.

1.2 A Brief History of the Universe

Our universe is vast not only in space, but also in time. Scientific measurements show that we live in a universe that is about 14 billion years old. To gain some perspective on this age, let's first explore our modern view of how we came to exist at this point in time, then consider how our human lifetimes compare to the age of the universe.

How did we come to be?

Figure 1.9 summarizes the history of the universe according to modern science. Follow the figure as you read through this section.

The Big Bang and the Expanding Universe Telescopic observations of distant galaxies show that the entire universe is **expanding,** meaning that average distances between galaxies are increasing with time. This fact implies that galaxies must have been closer together in the past, and if we go back far enough, we must reach the point at which the expansion began. We call this beginning the **Big Bang,** and scientists use the observed rate of expansion to calculate that it occurred about 14 billion years ago. The three cubes in the upper left corner of Figure 1.9 represent the expansion of a small piece of the entire universe through time.

The universe as a whole has continued to expand ever since the Big Bang, but on smaller scales the force of gravity has drawn matter together. Structures such as galaxies and galaxy clusters 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 galaxy clusters (and objects within them such as stars and planets) do *not* expand. The three cubes in Figure 1.9 illustrate this idea. Notice that as the cube as a whole grew larger, the matter within it clumped into galaxies and galaxy clusters. Most galaxies, including our own Milky Way, formed within a few billion years after the Big Bang.

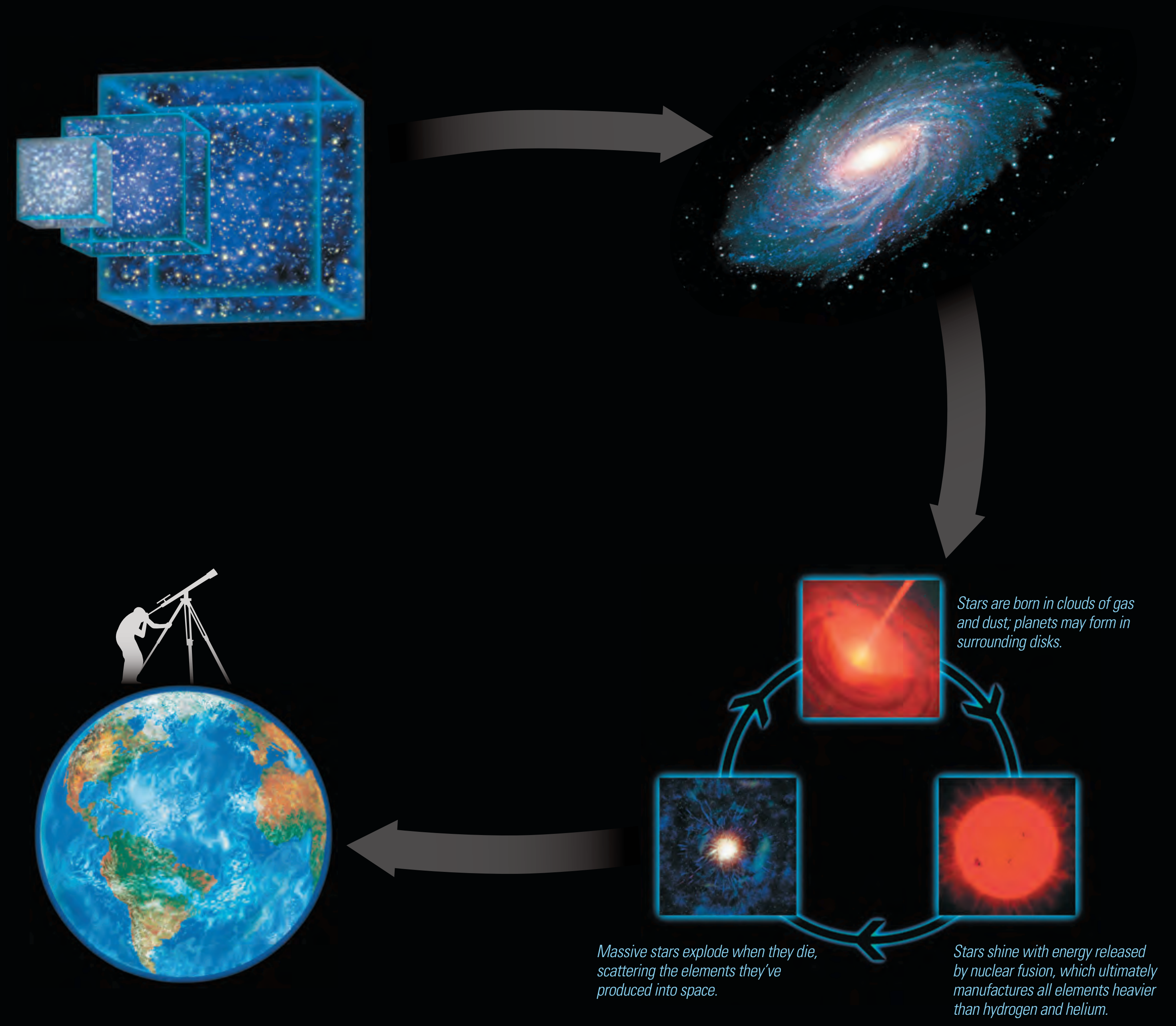
Stellar Lives and Galactic Recycling Within galaxies like the Milky Way, gravity drives the collapse of clouds of gas and dust to form stars and planets. Stars are not living organisms, but they nonetheless go through "life cycles." A star is born when gravity compresses the material in a cloud until the center becomes dense enough and hot enough to generate energy by **nuclear fusion,** the process in which lightweight atomic nuclei smash together and stick (or fuse) to make heavier nuclei. The star "lives" as long as it can shine with energy from fusion, and "dies" when it exhausts its usable fuel.

In its final death throes, a star blows much of its content back out into space. In particular, massive 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. Galaxies therefore function as cosmic recycling plants, recycling material expelled from dying stars into new generations of stars and planets. This cycle is illustrated in the lower right of Figure 1.9. Our own solar system is a product of many generations of such recycling.

Element Creation in Stars The recycling of stellar material is connected to our existence in an even deeper way. 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 of lithium). We and

Figure 1.9

Our Cosmic Origins



Birth of the Universe: The expansion of the universe began with the hot and dense Big Bang. The cubes show how one region of the universe has expanded with time. The universe continues to expand, but on smaller scales gravity has pulled matter together to make galaxies.

Galaxies as Cosmic Recycling Plants: The early universe contained only two chemical elements: hydrogen and helium. All other elements were made by stars and recycled from one stellar generation to the next within galaxies like our Milky Way.

Stars are born in clouds of gas and dust; planets may form in surrounding disks.

Stars shine with energy released by nuclear fusion, which ultimately manufactures all elements heavier than hydrogen and helium.

Massive stars explode when they die, scattering the elements they've produced into space.

Life Cycles of Stars: Many generations of stars have lived and died in the Milky Way.

Earth and Life: By the time our solar system was born, 4½ billion years ago, about 2% of the original hydrogen and helium had been converted into heavier elements. We are therefore "star stuff," because we and our planet are made from elements manufactured in stars that lived and died long ago.

Earth are made primarily of other elements, such as carbon, nitrogen, oxygen, and iron. Where did these other elements come from? Evidence shows that elements besides hydrogen and helium were manufactured by stars, some through the nuclear fusion that makes stars shine and others through nuclear reactions accompanying the explosions that end stellar lives.

By the time our solar system formed, about $4\frac{1}{2}$ billion years ago, earlier generations of stars had already converted about 2% of our galaxy's original hydrogen and helium into heavier elements. Therefore, the cloud that gave birth to our solar system was made of about 98% hydrogen and helium and 2% other elements. This 2% may sound small, but it was more than enough to make the small rocky planets of our solar system, including Earth. On Earth, some of these elements became the raw ingredients of life, which ultimately blossomed into 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 lived and died before the birth of our Sun. As astronomer Carl Sagan said, we are "star stuff."

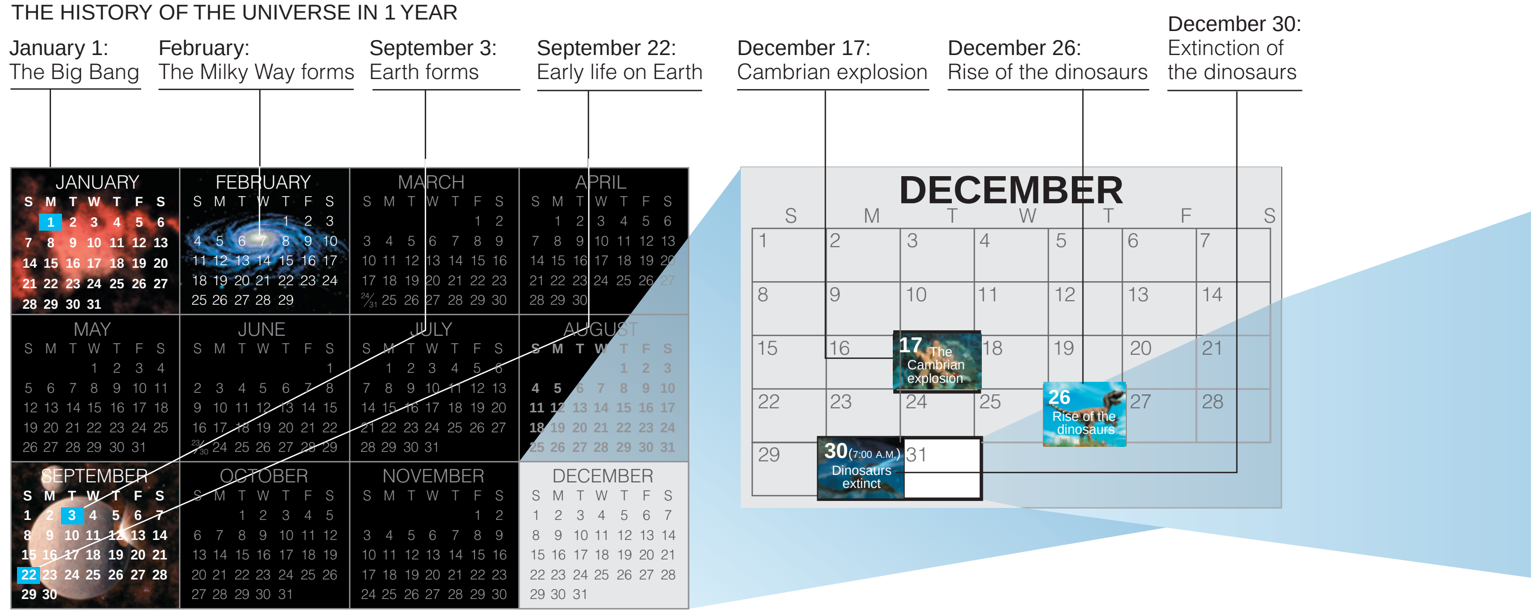
How do our lifetimes compare to the age of the universe?

We can put the 14-billion-year age of the universe into perspective by imagining this time compressed into a single year, so that each month represents a little more than 1 billion years. On this *cosmic calendar,* the Big Bang occurs at the first instant of January 1 and the present is the stroke of midnight on December 31 (**Figure 1.10**).

On this time scale, the Milky Way Galaxy probably formed 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 $4\frac{1}{2}$ 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. On the scale of the cosmic calendar, recognizable animals became prominent only in mid-December. Early dinosaurs appeared on the day after Christmas. Then, in a cosmic instant, the dinosaurs disappeared forever—probably because of the impact of an asteroid

Figure 1.10 | The cosmic calendar compresses the 14-billion-year history of the universe into 1 year, so that each month represents a little more than 1 billion years. (This cosmic calendar is adapted from a version created by Carl Sagan.)



or a comet [Section 6.3]. 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) began to walk 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.

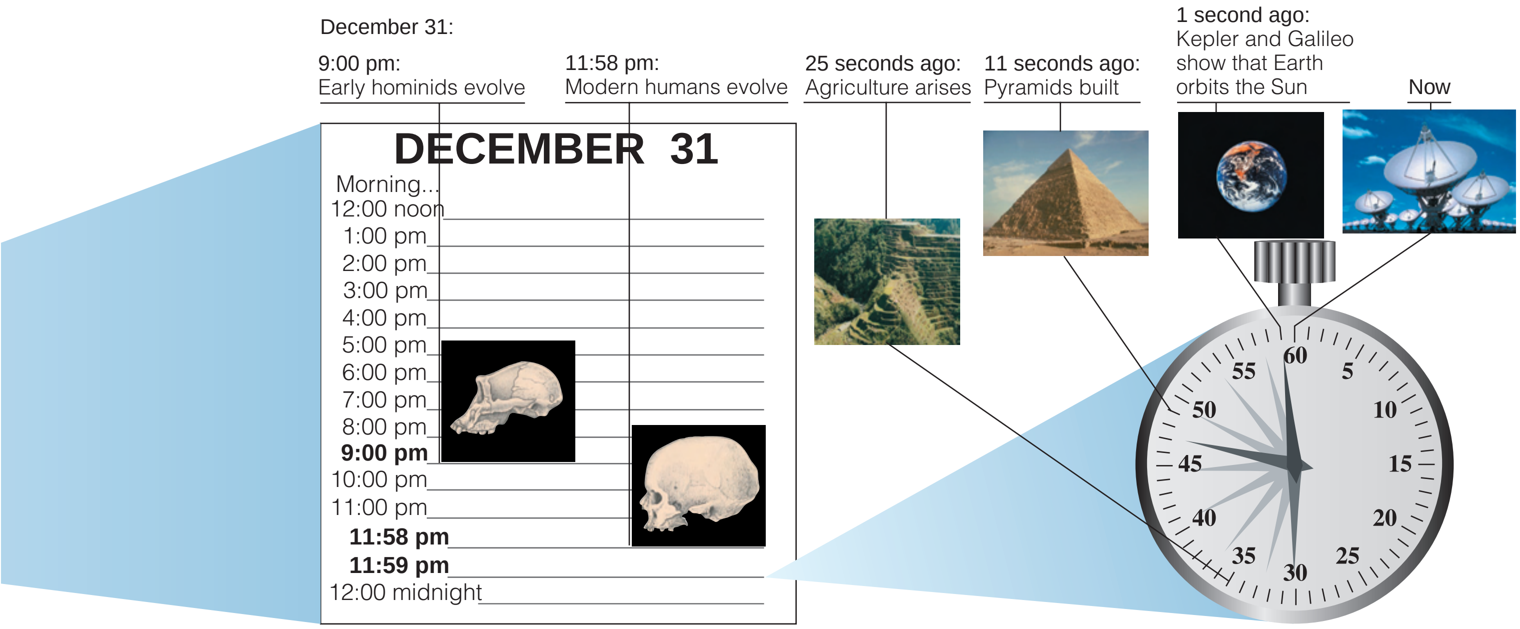
THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets

One of the goals of this book is to help you learn more about science in general as you study the science of astronomy. We will therefore conclude each chapter with a case study that illustrates the process of science in action. Here, we look at the process of scientific classification, a topic that made the news with the 2006 demotion of Pluto from *planet* to *dwarf planet.*

Science begins with observations of the world around us, and after observing we often try to classify the objects we find. Scientific classification helps us organize our thinking and provides a common language for discussion. Consider living things, which were long classified only as either plants or animals. This classification is clearly helpful, since "plant" immediately brings up a different mental picture than "animal." But it also has limitations: We now know that most living things are neither plants nor animals, but instead are members of diverse groups of microscopic organisms.

In this chapter, we have already classified objects into categories such as planets, stars, and galaxies. The box on page 5 provides basic definitions for these categories but does not explain *how* we came to classify objects in this way. You may notice that the definition of the term *planet* is particularly



complicated. The story behind this definition provides an excellent example of how scientists classify objects and how scientific classification must adapt to new discoveries.

What is a planet?

The difference between a star and a planet is not obvious from a casual glance at the night sky. In fact, the term *star* historically applied to almost any shining object in the night sky, including the planets and even the brief flashes of light known as "shooting stars" (or *meteors*), which we now know to be caused by comet dust entering Earth's atmosphere. To the naked eye, the difference between stars and planets becomes clear only if you observe the sky over a period of many days or weeks: Stars remain fixed in the patterns of the constellations, while planets appear to move slowly among the constellations of stars [Section 2.3].

Planets as Wanderers The word *planet* comes from the Greek for "wanderer," and in ancient times it applied to all objects that appear to move, or wander, among the constellations. The Sun and the Moon were counted as planets, because they move steadily through the constellations. Earth did *not* count as a planet, since it is not something we see in the sky and it was presumed to be stationary at the center of the universe. Ancient observers therefore recognized seven objects as planets: the Sun, the Moon, and the five planets that are easily visible to the naked eye (Mercury, Venus, Mars, Jupiter, and Saturn). The special status of these seven objects is still enshrined in the names of the seven days of the week. In English, only Sunday, Moonday, and Saturnday are obvious, but if you know a romance language like Spanish you'll be able to figure out the rest: Tuesday is Mars day (martes), Wednesday is Mercury day (miércoles), Thursday is Jupiter day (jueves), and Friday is Venus day (viernes).

This original definition of *planet* began to change about 400 years ago, when we learned that Earth is *not* the center of the universe but rather one of the objects that orbit the Sun. The term *planet* came to mean any object that orbits the Sun, which added Earth to the list of planets and removed the Sun and Moon (because the Moon orbits Earth). This definition successfully accommodated the planets Uranus and Neptune after their discoveries in 1781 and 1846, respectively.

A weakness of this definition became apparent as scientists began to discover asteroids, starting with the discovery of Ceres in 1801. Ceres was initially hailed as a new "planet," but as the number of known asteroids grew—and as we realized that asteroids were all much smaller than the traditional planets—scientists decided that these relatively small worlds should count only as "minor planets."

This division between "minor planets" and "planets" worked fine for more than a century, but recent discoveries have forced further changes in classification. For example, we now know that other stars have their own planets [Section 7.1], so the term *planet* is now used for these objects as well as for the planets that orbit our own Sun.

The Case of Pluto The most recent change in the definition of *planet* comes from the story of Pluto. Pluto was quickly given planetary status upon its discovery in 1930, mainly because astronomers overestimated its mass. Still, it was clear from the start that Pluto was a misfit among the known planets. Its 248-year orbit around the Sun is more elongated in shape than that of any other planet. Its orbit is also significantly tilted relative to the orbits of the other planets (**Figure 1.11**). It became even more of a misfit after

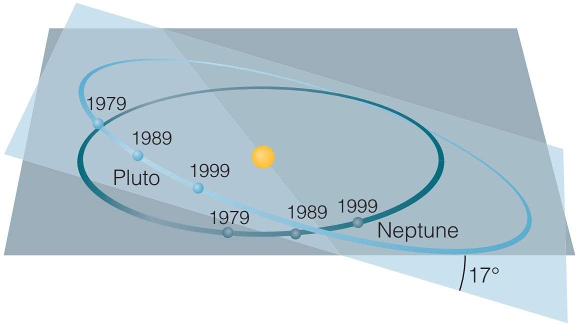


Figure 1.11 | Pluto's orbit is significantly elongated and tilted with respect to those of the other planets. It even comes closer to the Sun than Neptune for 20 years in each 248-year orbit, as was the case between 1979 and 1999. There's no danger of a collision, however, because Neptune completes exactly three orbits for every two of Pluto's orbits.

astronomers pinned down its mass and composition: Pluto is only about $\frac{1}{25}$ as massive as Mercury, smallest of the first eight planets, and its ice-rich composition is more similar to that of a comet than to that of any of the other planets.

Pluto's low mass, unusual orbit, and comet-like composition eventually began to cause controversy over its status as a planet. Scientists had known since the 1950s that many of the comets that we see in the inner solar system come from the same region of the solar system in which Pluto orbits (called the *Kuiper belt* [Section 4.1]). By the 1990s, telescope technology had reached the point where scientists could begin to observe this region of the solar system directly. Many Pluto-like objects were soon discovered, though for a while these objects were all smaller than Pluto. But in 2005, Caltech astronomer Mike Brown announced the discovery of an object that is slightly larger than Pluto, now known as Eris. Astronomers were forced to consider the question of whether Eris should count as a planet, and this led to reconsideration of the status of Pluto and of other objects that are close to Pluto in size.

At least three general ways of defining *planet* have been considered since Eris's discovery. The first would set Pluto's size as the minimum for a planet, thereby preserving Pluto's cultural status as the ninth planet. Eris would become the tenth planet, and objects discovered in the future would join the list only if they proved to be larger than Pluto. However, many scientists object that this definition is too arbitrary, as there is nothing special about Pluto's size.

A second possible definition would make planetary status depend solely on an object's physical characteristics. Several ways of doing this have been proposed; the most popular would define a planet as an object that is large enough for its own gravity to make it round. This definition would probably make dozens of Pluto-like objects count as planets (along with one or two asteroids), so our solar system might have 40 or more planets. Moreover, because there undoubtedly would be borderline cases, we might never be able to state the precise number of planets in our solar system. This definition also raises the question of whether large moons—including Earth's Moon—would count as planets because they are round.

The third idea defines *planet* so that neither Pluto nor Eris counts, leaving only eight planets in our solar system. This is the option chosen in 2006 by the International Astronomical Union (IAU), the organization responsible for astronomical names and definitions. The approved definition has some obvious quirks (such as defining a planet as something that orbits our Sun, which implies that no other star can have planets), but the underlying idea defines a planet as an object that (1) orbits a star (but is not itself a star); (2) is massive enough for its own gravity to make it round; and (3) dominates its orbital region. Objects that meet the first two criteria but not the third are designated *dwarf planets;* these include Pluto and Eris, which are round but share their orbital region with many similarly sized objects.

Does this definition make scientific sense? For the time being, the answer seems to be yes. **Figure 1.12** contrasts the sizes of various objects in our solar system. The eight planets clearly divide into two groups, while Pluto and Eris clearly belong to a different group. Nevertheless, we can envision future discoveries that could cause problems for the new definition. For example, what if

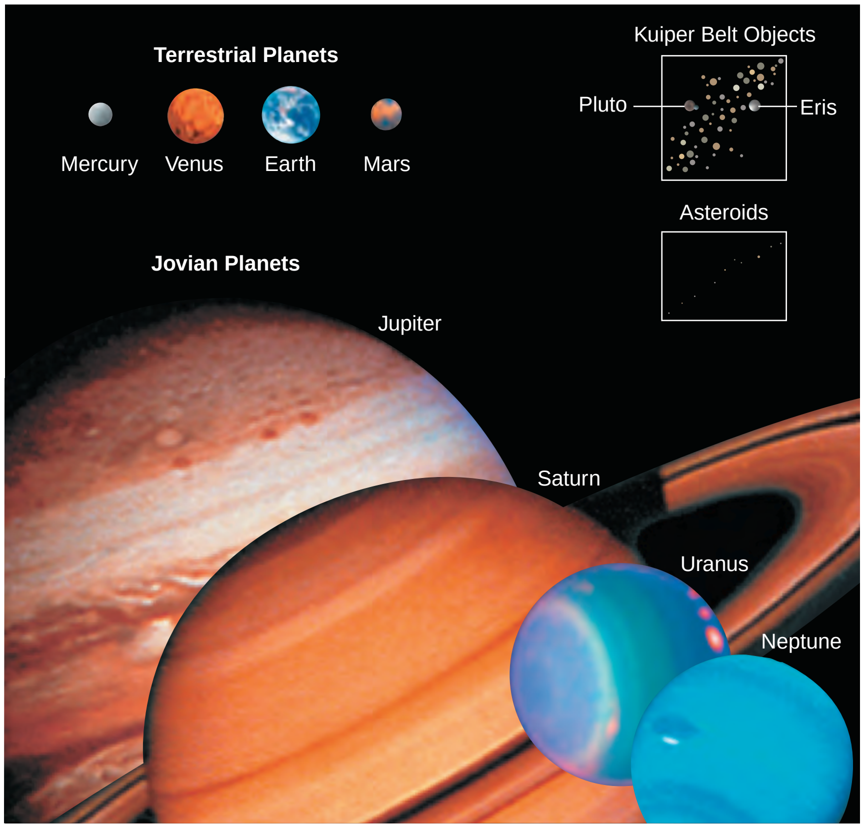


Figure 1.12 | Relative sizes of various objects in the solar system. Notice that the eight planets divide clearly into two groups, known as the *jovian planets* (Jupiter, Saturn, Uranus, and Neptune) and the *terrestrial planets* (Mercury, Venus, Earth, and Mars). Pluto and Eris clearly belong to a group of much smaller but more numerous objects.

we were to discover an Earth-size object orbiting in Pluto's region of the solar system; would its location mean it would count as a dwarf planet, even though it would be larger than Venus and Mars?

Perhaps the most important scientific idea to take away from this debate is that nature need not obey the classification systems we propose. Whether we call Pluto a planet, a dwarf planet, or a large comet may affect the way we think about it, but it does not change what it actually is. A key part of science is learning to adapt our own notions of organization to the underlying reality of nature. As we discover new things, we must sometimes change our definitions. Future astronomers may define *planet* differently than we do now.

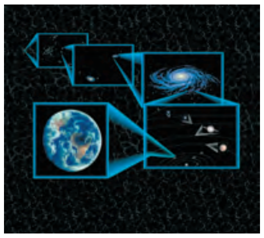
Think about it The 2009 IAU meeting will occur shortly after this book goes to press. Look for news reports on the meeting; was the definition of *planet* reconsidered? What's your opinion of the current definition?

Summary of Key Concepts

1.1 Our Place in the Universe

What is our place in the universe?

Earth is a planet orbiting the Sun. Our Sun is one of more than 100 billion stars in the **Milky Way Galaxy.** Our galaxy is one of about 40 galaxies in the **Local Group.** The Local Group is one small part of the **Local Supercluster,** which is one small part of the **universe.**



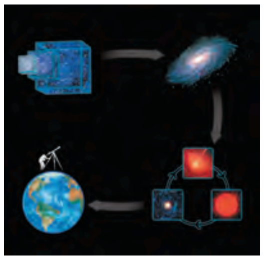
How big is the universe?

On a 1-to-10-billion scale, the Sun is the size of a grapefruit, Earth is a ball point about 15 meters away, and the nearest stars are thousands of kilometers away. Our galaxy has so many stars that it would take thousands of years just to count them. The **observable universe** contains some 100 billion galaxies, with a total number of stars comparable to the number of grains of dry sand on all the beaches on Earth.

1.2 A Brief History of the Universe

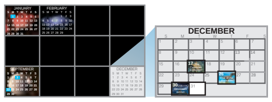
How did we come to be?

The universe began in the **Big Bang** and has been expanding ever since, except in localized regions where gravity has caused matter to collapse into galaxies and stars. The Big Bang essentially produced only two chemical elements: hydrogen and helium. All other elements have been produced by stars and recycled within galaxies from one generation of stars to the next. We and our planet are made of this recycled "star stuff."



How do our lifetimes compare to the age of the universe?

On a cosmic calendar that compresses the history of the universe into 1 year, human civilization is just a few seconds old, and a human lifetime lasts only a fraction of a second.

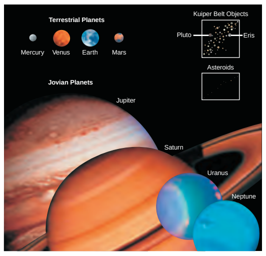


THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets

What is a planet?

The definition of the term *planet* has changed over time. It originally referred to objects that wandered among the constellations, but now applies to Earth and seven other objects in our solar system, while Pluto, Eris, and similar objects are classified as *dwarf planets*. The definition may yet change again, showing how scientific classification must adapt to new discoveries.



Investigations

Quick Quiz

Choose the best answer to each of the following; answers are in Appendix D. Explain your reasoning with one or more complete sentences.

1. Which of the following correctly lists our "cosmic address" from smallest to largest? (a) Earth, solar system, Milky Way Galaxy, Local Group, Local Supercluster, universe (b) Earth, solar system, Local Group, Local Supercluster, Milky Way Galaxy, universe (c) Earth, Milky Way Galaxy, solar system, Local Group, Local Supercluster, universe
2. An _astronomical unit_ is (a) any planet's average distance from the Sun. (b) Earth's average distance from the Sun. (c) any large astronomical distance.
3. A _light-year_ is (a) about 10 trillion kilometers. (b) the time it takes light to reach the nearest star. (c) the time it takes light to travel around the Sun.
4. The star Antares is 604 light-years away. If it explodes tonight, (a) we'll know because it will be brighter than the full Moon. (b) we'll know because debris from the explosion will rain down on us from space. (c) we won't know about it for another 604 years.
5. Could we see a galaxy that is 20 billion light-years away? (a) Yes, if we had a big enough telescope. (b) No, because it would be beyond the bounds of our observable universe. (c) No, because a galaxy could not possibly be that far away.
6. If we represent the solar system on a scale that allows us to walk from the Sun to Pluto in a few minutes, then (a) the planets are the size of basketballs and the nearest stars are a few miles away. (b) the planets are marble size or smaller and the nearest stars are thousands of miles away. (c) the planets are microscopic and the stars are millions of miles away.
7. The number of stars in the Milky Way Galaxy is roughly (a) 100,000. (b) 100 million. (c) 100 billion.
8. When we say the universe is _expanding,_ we mean that (a) everything in the universe is growing in size. (b) the average distance between galaxies is growing with time. (c) the number of stars in the universe is growing with time.
9. The _Big Bang_ is the name astronomers give to (a) the explosion that occurs when a star dies. (b) the largest explosion ever observed. (c) the birth of the universe.
10. We are "star stuff" in the sense that (a) we are made of elements that were produced in stars. (b) our bodies have the same chemical composition as stars. (c) we are born, live, and die, just like stars.
11. The age of our solar system is about (a) $\frac{1}{3}$ of the age of the universe. (b) $\frac{3}{4}$ of the age of the universe. (c) the same as the age of the universe.
12. The event that triggered the change in Pluto's status from planet to dwarf planet was the discovery that (a) it is smaller than the planet Mercury. (b) it has a comet-like composition of ice and rock. (c) it is not the largest object in its region of the solar system.

Short-Answer/Essay Questions

Explain all answers clearly, using complete sentences and proper essay structure if needed. An asterisk (*) designates a quantitative problem, for which you should show all your work.

13. _Our Cosmic Origins._ Write one to three paragraphs summarizing why we could not be here if the universe did not contain both stars and galaxies.
14. _Alien Technology._ Some people believe that Earth is being visited by aliens from other star systems. If this is true, how would the alien technology compare to our own? Using ideas of scale introduced in this chapter, write one to two paragraphs to give a sense of the technological difference.
15. _Looking for Evidence._ This chapter discussed the scientific story of the universe but not the evidence that backs it up. Choose one idea from this chapter—such as the idea that there are billions of galaxies, that the universe was born in the Big Bang, or that we are "star stuff"—and briefly discuss the type of evidence you would like to see before accepting the idea. (Hint: You can look ahead in the book to see the evidence presented in later chapters.)
16. _The Value of Classification._ Section 1.3 discussed difficulties that can arise with attempts to define scientific classifications precisely, such as those that occur with the term _planet._ Make a bullet list of pros and cons (at least three of each) to having classification schemes. Then write a one-paragraph summary stating your opinion of the value (or lack of value) of scientific classification.
17. _The Cosmic Perspective._ Write a one-page essay describing how the ideas presented in this chapter affect your perspectives on your own life and on human civilization.

*18. _Light-Minute._ Just as a light-year is the distance that light can travel in 1 year, a light-minute is the distance that light can travel in 1 minute. What is a light-minute in kilometers?

*19. _Sunlight._ Use the speed of light and the Earth–Sun distance of 1 AU to calculate how long it takes light to travel from the Sun to Earth.

*20. _Cosmic Calendar._ The cosmic calendar condenses the 14-billion-year history of the universe into 1 year. How long does 1 second represent on the cosmic calendar?

*21. _Saturn vs. the Milky Way._ Photos of Saturn with its rings can look so similar to photos of galaxies that children often think they are similar objects, but of course galaxies are far larger. About how many times larger in diameter is the Milky Way Galaxy than Saturn's rings? (_Data:_ Saturn's rings are 270,000 km in diameter; the Milky Way is 100,000 light-years in diameter.)

*22. _Galactic Rotation._ Our solar system is located about 28,000 light-years from the galactic center and orbits the center once every 230 million years. How fast are we traveling around the galaxy, in km/hr?