Chapter 22 The Origin of Earth and the Solar System

Learning Objectives

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe what happened during the big bang, and explain how we know it happened
- Explain how clouds of gas floating in space can turn into stars, planets, and solar systems
- Describe the types of objects that are present in our solar system, and why they exist where they do
- Outline the early stages in Earth's history, including how it developed its layered structure, and where its water and atmosphere came from
- Explain how the Moon formed, and how we know
- Summarize the progress so far in the hunt for habitable-zone planets outside of our solar system
- Explain why the planetary systems we have discovered so far raise questions about our model of how the solar system formed

The story of how Earth came to be is a fascinating contradiction. On the one hand, many, many things had to go just right for Earth to turn out the way it did and develop life. On the other hand, the formation of planets similar to Earth is an entirely predictable consequence of the laws of physics, and it seems to have happened more than once.

We will start Earth's story from the beginning—the *very* beginning—and learn why generations of stars had to be born and then die explosive deaths before Earth could exist. We will look at what it takes for a star to form, and for objects to form around it, as well as why the nature of those objects depends on how far away from the central star they form.

Earth spent its early years growing up in a very rough neighbourhood, and we will discuss how Earth's environment influenced its development, including how it got its moon from what was quite literally an Earth-shattering blow. This chapter will also discuss the hunt for Earth-like **exoplanets** (planets that exist outside of our solar system).

22.1 Starting with a Big Bang

Karla Panchuk

According to the **big bang theory**, the universe blinked violently into existence 13.77 billion years ago (Figure 22.1.1). The big bang is often described as an explosion, but imagining it as an enormous fireball isn't accurate. The big bang involved a sudden expansion of matter, energy, and space from a single point. The kind of Hollywood explosion that might come to mind involves expansion of matter and energy *within* space, but during the big bang, space *itself* was created.

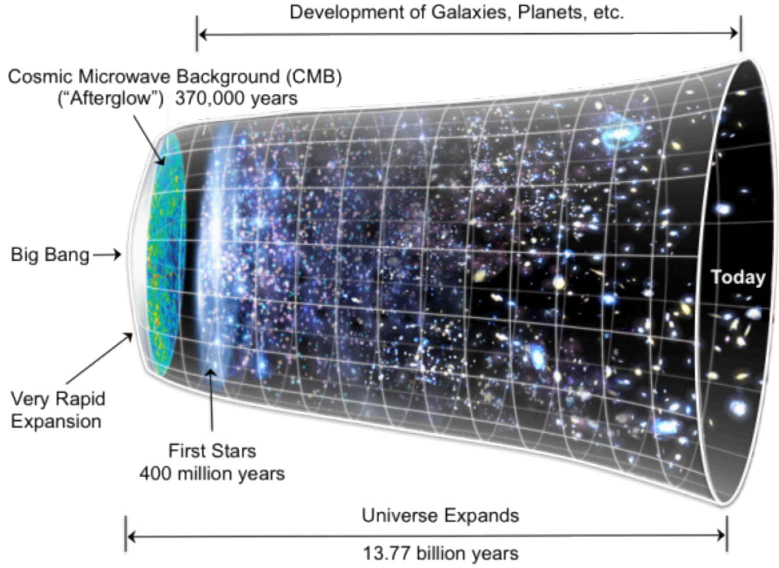

Figure 22.1.1 The big bang. The universe began 13.77 billion years ago with a sudden expansion of space, matter, and energy, and it continues to expand today.

At the start of the big bang, the universe was too hot and dense to be anything but a sizzle of particles smaller than atoms, but as it expanded, it also cooled. Eventually some of the particles collided and stuck together. Those collisions produced hydrogen and helium, the most common elements in the universe, along with a small amount of lithium.

You may wonder how a universe can be created out of nothing, or how we can know that the big bang happened at all. Creating a universe out of nothing is mostly beyond the scope of this chapter, but there is a way to think about it. The particles that make up the universe have opposites that cancel each other out, similar to the way that we can add the numbers 1 and −1 to get zero (also known as "nothing"). As far as the math goes, having zero is exactly the same as having a 1 and a −1. It is also exactly the same as having a 2 and a −2, a 3 and a −3, two −1s and a 2, and so on. In other words, *nothing* is really the potential for *something* if you divide it into its opposite parts. As for how we can know that the big bang happened at all, there are very good reasons to accept that it is indeed how our universe came to be.

Looking back to the early stages of the big bang

The notion of seeing the past is often used metaphorically when we talk about ancient events, but in this case it is meant literally. In our everyday experience, when we watch an event take place, we perceive that we are watching it as it unfolds in real time. In fact, this isn't true. To see the event, light from that event must travel to our eyes. Light travels very rapidly, but it does not travel instantly. If we were watching a digital clock 1 m away from us change from 11:59 a.m. to 12:00 p.m., we would actually see it turn to 12:00 p.m. three billionths of a second after it happened. This isn't enough of a delay to cause us to be late for an appointment, but the universe is a very big place, and the "digital clock" in question is often much, much farther away. In fact, the universe is so big that it is convenient to describe distances in terms of **light years**, or the distance light travels in one year. What this means is that light from distant objects takes so long to get to us that we see those objects as they were at some considerable time in the past. For example, the star Proxima Centauri is 4.24 light years from the sun. If you viewed Proxima Centauri from Earth on January 1, 2015, you would actually see it as it appeared in early October 2010.

We now have tools that are powerful enough to look deep into space and see the arrival of light from early in the universe's history. Astronomers can detect light from approximately 375,000 years after the big bang is thought to have occurred. Physicists tell us that if the big bang happened, then particles within the universe would still be very close together at this time. They would be so close that light wouldn't be able to travel far without bumping into another particle and getting scattered in another direction. The effect would be to fill the sky with glowing fog, the "afterglow" from the formation of the universe (Figure 22.1.1).

In fact, this is exactly what we see when we look at light from 375,000 years after the big bang. The fog is referred to as the **cosmic microwave background** (or CMB), and it has been carefully mapped throughout the sky (Figure 22.1.2). The map displays the cosmic microwave background as temperature variations, but these variations translate to differences in the density of matter in the early universe. The red patches are the highest density regions and the blue patches are the lowest density. Higher density regions represent the eventual beginnings of stars and planets. The map in Figure 22.1.2 has been likened to a baby picture of the universe.

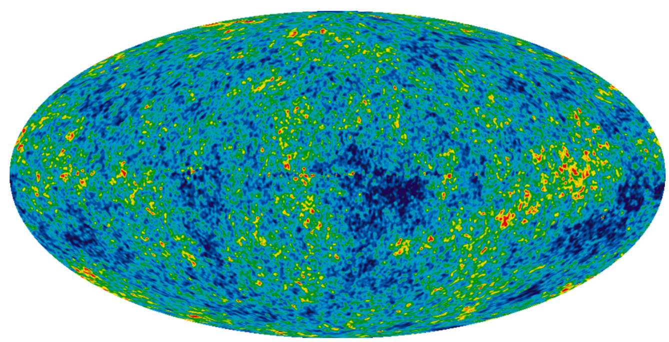

Figure 22.1.2 Cosmic microwave background (CMB) map of the sky, a baby picture of the universe. The CMB is light from 375,000 years after the big bang. The colours reveal variations in density. Red patches have the highest density and blue patches have the lowest density. Regions of higher density eventually formed the stars, planets, and other objects we see in space today.

The big bang is still happening, and we can see the universe expanding

The expansion that started with the big bang never stopped. It continues today, and we can see it happening by observing that large clusters of billions of stars, called **galaxies**, are moving away from us. (The exception is the Andromeda galaxy with which we are on a collision course.) The astronomer Edwin Hubble came to this conclusion when he observed that the light from other galaxies was red-shifted. The **red shift** is a consequence of the Doppler effect. This refers to how we see waves when the object that is creating the waves is moving toward us or away from us.

Before we get to the Doppler effect as it pertains to the red shift, let's see how it works on something more tangible. The duckling swimming in Figure 22.1.3 is generating waves as it moves through the water. It is generating waves that move forward as well as back, but notice that the ripples ahead of the duckling are closer to each other than the ripples behind the duckling. The distance from one ripple to the next is called the **wavelength**. The wavelength is shorter in the direction that the duckling is moving, and longer as the duckling moves away.

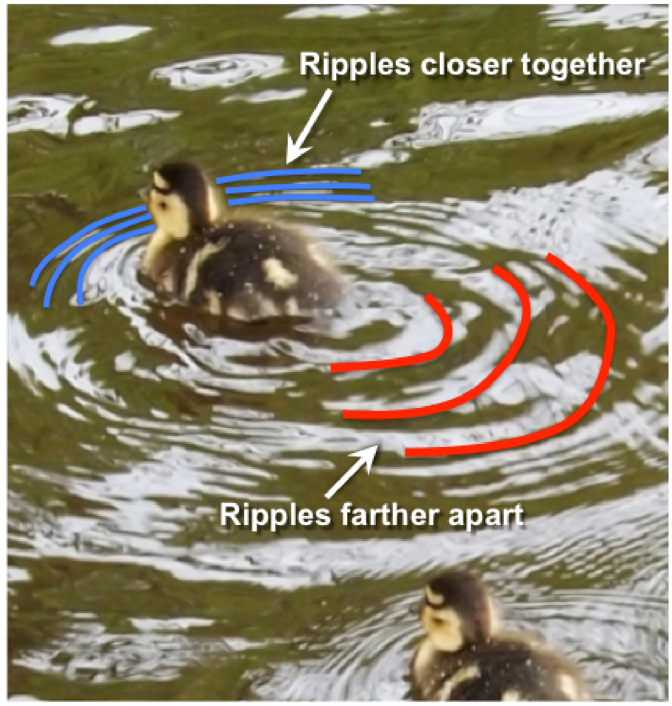

Figure 22.1.3 Duckling illustrates the Doppler effect in water. The ripples made in the direction the duckling is moving (blue lines) are closer together than the ripples behind the duckling (red lines).

When waves are in air as sound waves rather than in water as ripples, the different wavelengths manifest as sounds with different pitches—the short wavelengths have a higher pitch, and the long wavelengths have a lower pitch. This is why the pitch of a car's engine changes as the car races past you.

For light waves, wavelength translates to colour (Figure 22.1.4). In the spectrum of light that we can see, shorter wavelengths are on the blue end of the spectrum, and longer wavelengths are on the red end of the spectrum. Does this mean that galaxies look red because they are moving away from us? No, but the colour we see is shifted toward the red end of the spectrum and longer wavelengths.

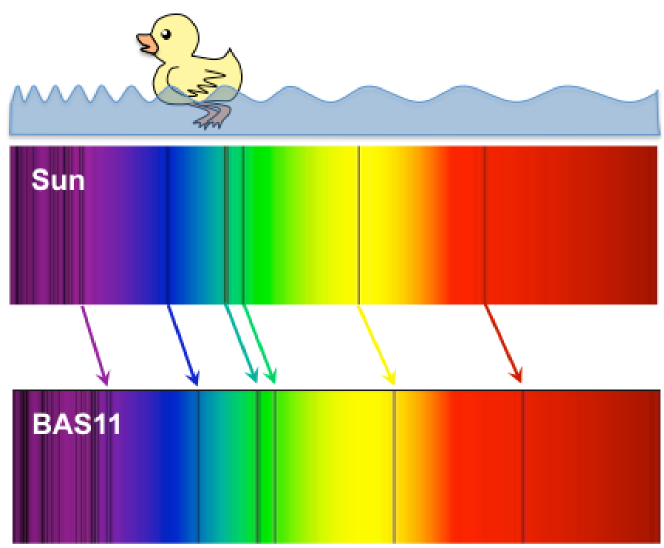

Figure 22.1.4 Red shift in light from the supercluster BAS11 compared to the sun's light. Black lines represent wavelengths absorbed by atoms (mostly H and He). For BAS11 the black lines are shifted toward the red end of the spectrum compared to the Sun.

Notice that the sun's spectrum in the upper part of Figure 22.1.4 has some black lines in it. The black lines are there because some colours are missing in the light we get from the Sun. Different elements absorb light of specific wavelengths, and many of the black lines in Figure 22.1.4 represent colours that are absorbed by hydrogen and helium within the Sun. This means the black lines are like a bar code that can tell us what a star is made of. The lower spectrum in Figure 22.1.4 is the light coming from BAS11, an enormous cluster of approximately 10,000 galaxies located 1 billion light years away. The black lines represent the same elements as in the Sun's spectrum, but they are shifted to the right toward the red end of the spectrum because BAS11 is moving away from us as the universe continues to expand. So to summarize, because almost all of the galaxies we can see have light that is red-shifted, it means they are all moving away from us. In fact, the farther away they are, the faster they are going. This is evidence that the universe is still expanding.

Media Attributions

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22.2 Forming Planets from the Remnants of Exploding Stars

Karla Panchuk

If we were to take an inventory of the elements that make up Earth, we would find that 95% of Earth's mass comes from only four elements: oxygen, magnesium, silicon, and iron. Most of the remaining 5% comes from aluminum, calcium, nickel, hydrogen, and sulphur. We know that the big bang made hydrogen, helium, and lithium, but where did the rest of the elements come from?

The answer is that the other elements were made by stars. Sometimes stars are said to "burn" their fuel, but burning is not at all what is going on within stars. The burning that happens when wood in a campfire is turned to ash and smoke is a chemical reaction—heat causes the atoms that were in the wood and in the surrounding atmosphere to exchange partners. Atoms group in different ways, but the atoms themselves do not change. What stars do is change the atoms. The heat and pressure within stars cause smaller atoms to smash together and fuse into new, larger atoms. For example, when hydrogen atoms smash together and fuse, helium is formed. Large amounts of energy are released when some atoms fuse and that energy is what causes stars to shine.

It takes larger stars to make elements as heavy as iron and nickel. Our Sun is an average star; after it uses up its hydrogen fuel to make helium, and then some of that helium is fused to make small amounts of beryllium, carbon, nitrogen, oxygen, and fluorine, it will be at the end of its life. It will stop making atoms and will cool down and bloat until its middle reaches the orbit of Mars. In contrast, large stars end their lives in spectacular fashion, exploding as supernovae and casting off newly formed atoms—including the elements heavier than iron—into space. It took many generations of stars creating heavier elements and casting them into space before heavier elements were abundant enough to form planets like Earth.

Until recently, astronomers have only been able to see stars that already contain heavier elements in small amounts, but not the first-generation stars that started out before any of the heavier elements were produced. That changed in June of 2015 when it was announced that a distant galaxy called CR7 had been found that contained stars made only of hydrogen and helium. The galaxy is so far away that it shows us a view of the universe from only 800 million years after the big bang.[1]

1. Read more about the discovery of CR7 here: "Astronomers spot first-generation stars, made from big bang," (http://bit.ly/CR7galaxy)

22.3 How to Build a Solar System

Karla Panchuk

A **solar system** consists of a collection of objects orbiting one or more central stars. All solar systems start out the same way. They begin in a cloud of gas and dust called a **nebula**. Nebulae are some of the most beautiful objects that have been photographed in space, with vibrant colours from the gases and dust they contain, and brilliant twinkling from the many stars that have formed within them (Figure 22.3.1). The gas consists largely of hydrogen and helium, and the dust consists of tiny mineral grains, ice crystals, and organic particles.

Step 1: Collapse a nebula

Figure 22.3.1 Photograph of a nebula. The Pillars of Creation within the Eagle Nebula viewed in visible light (left) and near infrared light (right). Near infrared light captures heat from stars and allows us to view stars that would otherwise be hidden by dust. This is why the picture on the right appears to have more stars than the picture on the left.

A solar system begins to form when a small patch within a nebula (small by the standards of the universe, that is) begins to collapse upon itself. Exactly how this starts isn't clear, although it might be triggered by the violent behaviour of nearby stars as they progress through their life cycles. Energy and matter released by these stars might compress the gas and dust in nearby neighbourhoods within the nebula.

Once it is triggered, the collapse of gas and dust within that patch continues for two reasons. One of those reasons is that gravitational force pulls gas molecules and dust particles together. But early in the process, those particles are very small, so the gravitational force between them isn't strong. So how do they come together? The answer is that dust first accumulates in loose clumps for the same reason dust bunnies form under your bed: static electricity. Given the role of dust bunnies in the early history of the solar system, one might speculate that an accumulation of dust bunnies poses a substantial risk to one's home (Figure 22.3.2). In practice, however, this is rarely the case.

Step 2: Make a disk and put a star at its centre

As the small patch within a nebula condenses, a star begins to form from material drawn into the centre of the patch, and the remaining dust and gas settle into a disk that rotates around the star. The disk is where planets eventually form, so it's called a **protoplanetary disk**. In Figure 22.3.3 the image in the upper left shows an artist's impression of a protoplanetary disk, and the image in the upper right shows an actual protoplanetary disk surrounding the star HL Tauri. Notice the dark rings in the protoplanetary disk. These are gaps where planets are beginning to form. The rings are there because incipient planets are beginning to collect the dust and gas in their orbits. There is an analogy for this in our own solar system, because the dark rings are akin to the gaps in the rings of Saturn (Figure 22.3.3, lower left), where moons can be found (Figure 22.3.3, lower right).

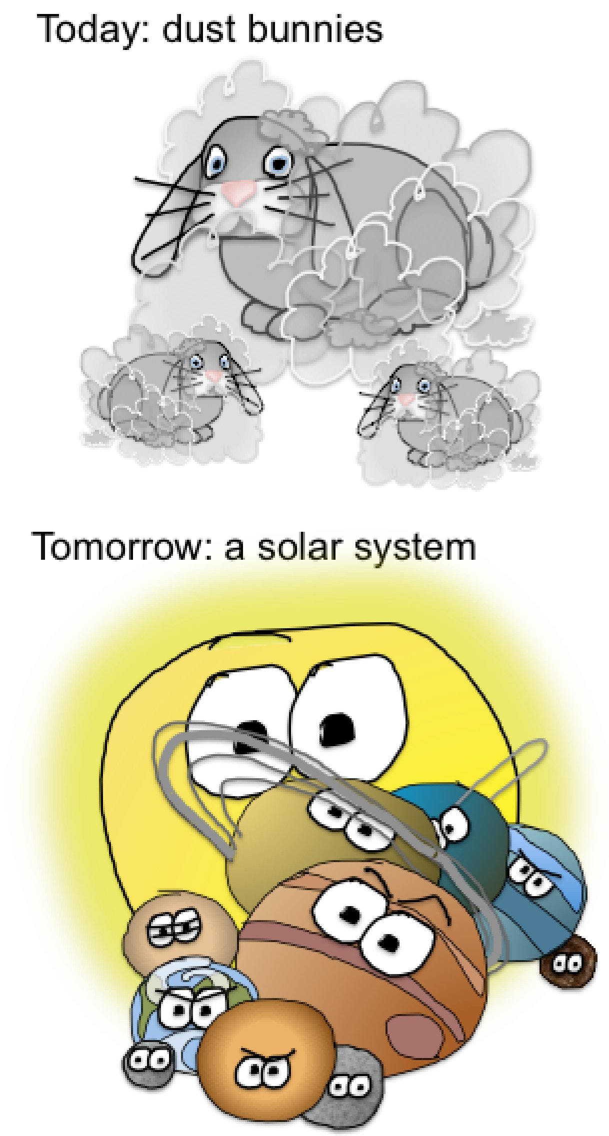


Figure 22.3.2 Public service announcement. If you don't think housekeeping is important, then you don't understand the gravity of the situation.

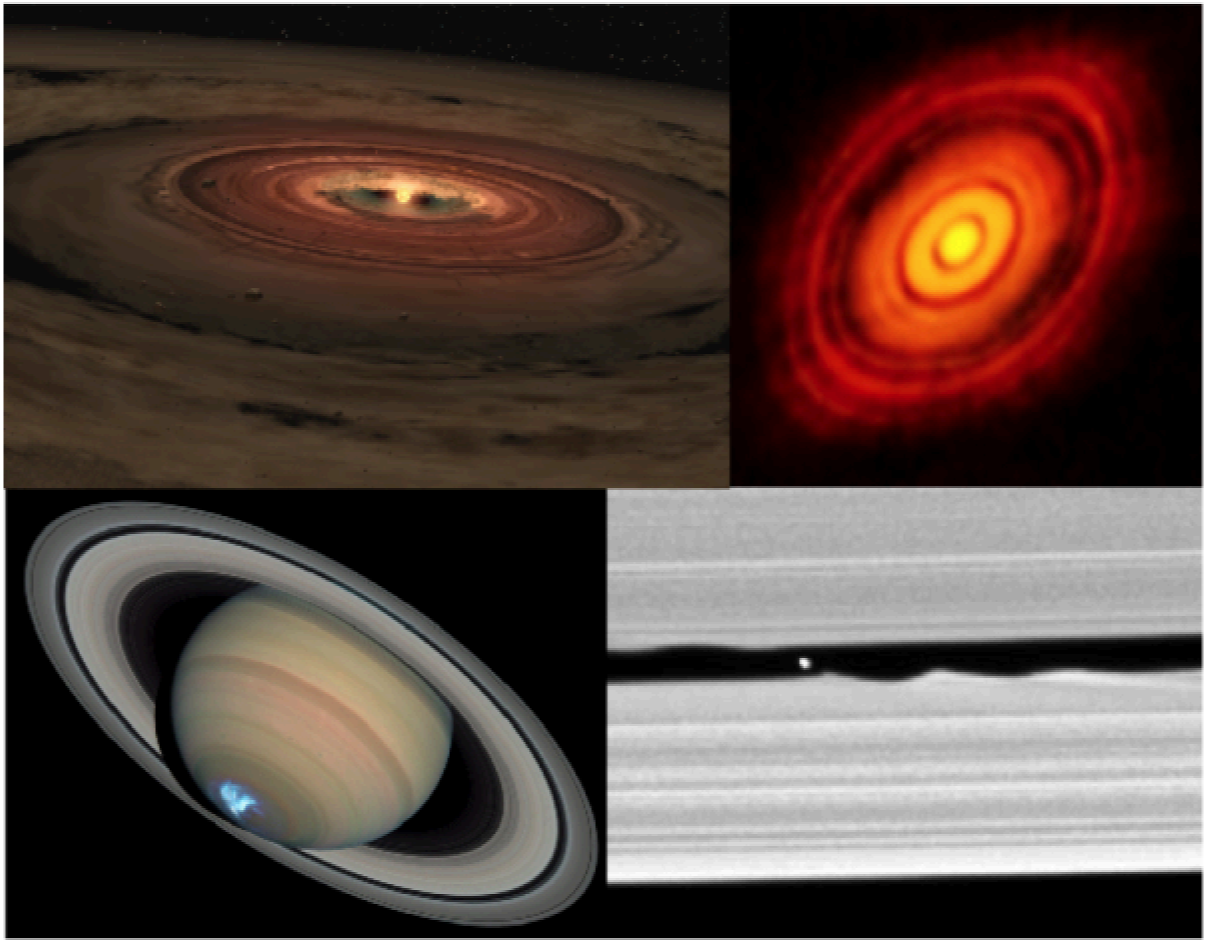


Figure 22.3.3 Protoplanetary disks and Saturn's rings. Upper left: An artists impression of a protoplanetary disk containing gas and dust, surrounding a new star. Upper right: A photograph of the protoplanetary disk surrounding HL Tauri. The dark rings within the disk are thought to be gaps where newly forming planets are sweeping up dust and gas. Lower left: A photograph of Saturn showing similar gaps within its rings. The bright spot at the bottom is an aurora, similar to the northern lights on Earth. Lower right: a close-up view of a gap in Saturn's rings showing a small moon as a white dot.

Step 3: Build some planets

In general, planets can be classified into three categories based on what they are made of (Figure 22.3.4). **Terrestrial planets** are those planets like Earth, Mercury, Venus, and Mars that have a core of metal surrounded by rock. **Jovian planets** (also called **gas giants**) are those planets like Jupiter and Saturn that consist predominantly of hydrogen and helium. **Ice giants** are planets such as Uranus and Neptune that consist largely of water ice, methane (CH_4) ice, and ammonia (NH_3) ice, and have rocky cores. Often, the ice giant planets Uranus and Neptune are grouped with Jupiter and Saturn as gas giants; however, Uranus and Neptune are very different from Jupiter and Saturn.

These three types of planets are not mixed together randomly within our solar system. Instead they occur in a systematic way, with terrestrial planets closest to the sun, followed by the Jovian planets and then the ice giants (Figure 22.3.5). Smaller **solar system** objects follow this arrangement as well. The **asteroid belt** contains bodies of rock and metal. Bodies ranging from metres to hundreds of metres in diameter are classified as **asteroids**, and smaller bodies are referred to as **meteoroids**. In contrast, the **Kuiper belt** (*Kuiper* rhymes with *piper*), and the **Oort cloud** (*Oort* rhymes with *sort*), which are at the outer edge of the solar system, contain bodies composed of large amounts of ice in addition to rocky fragments and dust. (We will talk more about smaller solar system objects in a moment.)

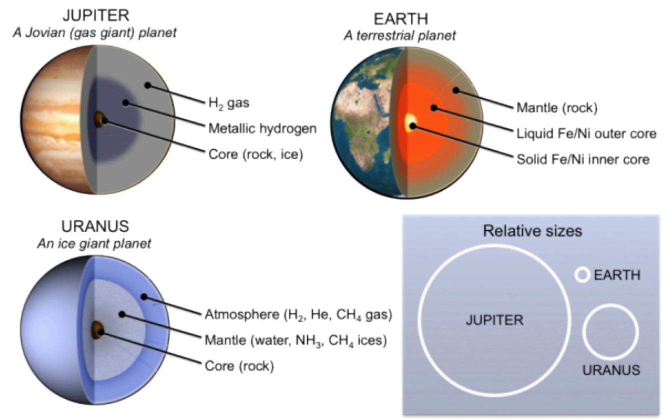


Figure 22.3.4 Three types of planets. Jovian (or gas giant) planets, such as Jupiter, consist mostly of hydrogen and helium. They are the largest of the three types. Ice giant planets, such as Uranus, are the next largest. They contain water, ammonia, and methane ice. Terrestrial planets such as Earth are the smallest, and they have metal cores covered by rocky mantles.

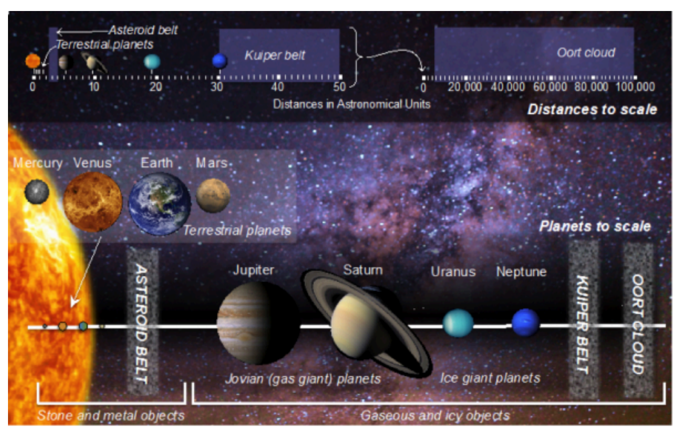


Figure 22.3.5 Our solar system. Top: The solar system shown with distances to scale. Distances are in astronomical units (AU), where 1 AU is the average distance from Earth to the Sun. The edge of the Kuiper belt extends to 50 AU (7.5 billion km), but this distance is minuscule compared to the size of the solar system as a whole, which extends to the edge of the Oort cloud, thought to be 15 trillion km away. Bottom: Solar system with the Sun and planets to scale. The gas giants are the largest planets, followed by the ice giants, and then the terrestrial planets. Note that the planets in this diagram likely do not reflect the entire population of planets in our solar system because evidence suggests that large planets are present beyond the Kuiper belt.

Part of the reason for this arrangement is the **frost line** (also referred to as the **snow line**). The frost line separated the inner part of the protoplanetary disk closer to the sun, where it was too hot to permit anything but silicate minerals and metal to crystalize, from the outer part of the disk farther from the Sun, where it was cool enough to allow ice to form. As a result, the objects that formed in the inner part of the protoplanetary disk consist largely of rock and metal, while the objects that formed in the outer part consist largely of gas and ice. The young sun blasted the solar system with raging **solar winds** (winds made up of energetic particles), which helped to drive lighter molecules toward the outer part of the protoplanetary disk.

The objects in our solar system formed by **accretion**. Early in this process, particles collected in fluffy clumps because of static electricity. As the clumps grew larger, gravity became more important and collected clumps into solid masses, and solid masses into larger and larger bodies. If you were one of these bodies in the early solar system, and participating in the accretion game with the goal of becoming a planet, you would have to follow some key rules:

- Keep your velocity just right. If you move too fast and collide with another body, you both smash up and have to start again. If you move slowly enough, gravity will keep you from bouncing off each other and you can grow larger.

- Your distance from the Sun will determine how big you can get. If you are closer, there is less material for you to collect than if you are farther away.
- To begin with, you can only collect mineral and rock particles. You have to grow above a certain mass before your gravity is strong enough to hang onto gas molecules, because gas molecules are very light.
- As your mass increases, your gravity becomes stronger and you can grab material from farther away. The bigger you are, the faster you grow.

You would also have to watch out for some dangers:

- In the early stages of the game, the protoplanetary disk is turbulent, and you and other objects can get thrown into different orbits or at each other. This might be a good thing, or it might not, depending on how the rules above apply to you.
- If the game progresses to the point where there is no more material within your reach and you are not yet a planet, then it's game over.
- If you slow down too much (e.g., from bumping into other objects), you could spiral into the Sun (game over).
- If another planet gets big enough, it can:
    - Rip you apart and then swing the pieces around so fast that for the rest of the game you collide too hard with other pieces to grow any bigger (game over)
    - Fling you out of the solar system (game over)
    - Grab you for itself (game over)
    - Trap you in an orbit around it, turning you into a moon (game over, and incredibly humiliating)

The outcome of the game is evident in Figure 22.3.5. Today eight official winners are recognized, with Jupiter taking the grand prize, followed closely by Saturn. Both planets have trophy cases with more than 60 moons each, and each has a moon that is larger than Mercury. Prior to 2006, Pluto was also counted a winner, but in 2006 a controversial decision revoked Pluto's planet status. The reason was a newly formalized definition of a planet, which stated that an object can only be considered a planet if it is massive enough to have swept its orbit clean of other bodies. Pluto is situated within the icy clutter of the Kuiper belt, so it does not fit this definition. Pluto's supporters have argued that Pluto should have been grandfathered in, given that the definition came after Pluto was declared a planet, but to no avail. Pluto has not given up, and on July 13, 2015, it launched an emotional plea with the help of the NASA's New Horizons probe. New Horizons sent back images of Pluto's heart (Figure 22.3.6). On closer inspection, Pluto's heart was discovered to be broken.

The rules and dangers of the planet-forming game help to explain many features of our solar system today.

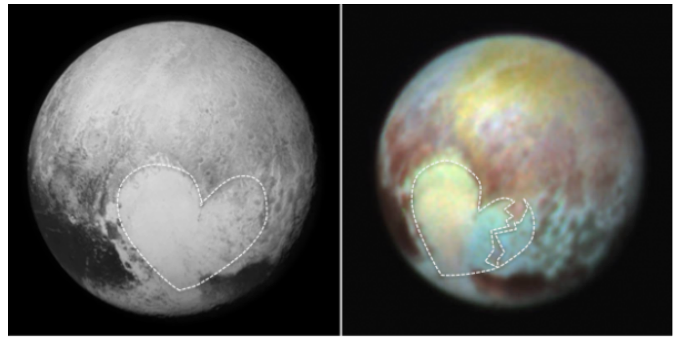


Figure 22.3.6 Photographs of Pluto. Left: The heart-shaped region called Tombaugh Regio is outlined. This region is named after Pluto's discoverer, Clyde Tombaugh.

- Proximity to the Sun explains why the terrestrial planets are so much smaller than the gas giant and ice giant planets.
- Mars is smaller than it should be, given the rule that distance from the Sun determines how much material a body can accumulate, and this can be explained by its proximity to Jupiter. Jupiter's immense gravity interfered with Mars' ability to accrete. Further evidence of Jupiter's interference is the debris field that forms the asteroid belt. From time to time, Jupiter still flings objects from the asteroid belt out into other parts of the solar system, some of which have collided with Earth to catastrophic effect.
- The Kuiper belt is an icy version of the asteroid belt, consisting of fragments left over from the early solar system. The material in the Kuiper belt is scattered because of Neptune's gravity. From time to time, Jupiter interferes here as well, flinging Kuiper belt objects toward the Sun and into orbit. As these objects approach the Sun, the Sun causes dust and gas to be blasted from their surface, forming tails. We know these objects as comets.
- Comets may also come from the Oort cloud where gravitational forces from outside of the solar system can hurl objects from the Oort cloud toward the Sun.

Exercise 22.1 How do we know what other planets are like inside?

The densities of planets give us important clues about the planets' compositions. For example, in our solar system, Earth (a terrestrial planet) has a density of 5.51 grams per cubic centimetre (g/cm^3), but Jupiter (a gas giant) has a density of 1.33 g/cm^3. We can also use density to determine something about the interior structures of planets. In this exercise, you will determine how much of each terrestrial planet is made up of core, and translate that result to a diagram for easy comparison.

It is useful to approximate the structure of a terrestrial planet as having two parts: a metal core and a rocky mantle. If we know the density of the planet as a whole, and the densities of the materials making up the rocky mantle and the core, we can find out how much of the planet is core and how much is rocky. The density of the planet is the sum of the percent having the density of the core and the percent having the density of rock. This can be written as follows:

planet density = % core/100 x core density + (1− %core ÷ 100) × rock density

Rearranging the equation gives us:

% core = (planet density − rock density)/ (core density − rock density) × 100

Step 1.

Find the percent core for each of the terrestrial planets using the data in Tables 22.1 and 22.2. For our calculations, the planet density will be the **uncompressed density** of the planet. Uncompressed density is the density after removing the effects of gravity squeezing the planet together. (Notice that the density we mentioned for Earth is 5.51 g/cm^3, but Earth's uncompressed density is only 4.05 g/cm^3.) The first one is done for you.

Table 22.1 Core and mantle density from meteorites

Description	**Density (g/cm^3)**	**Source**	**Why?**
Core density	8.00	iron meteorites	Iron meteorites come from the cores of broken up asteroids and planets and approximate what the density of Earth's core would be without gravitational squeezing.
Rocky mantle density	3.25	HED* stony meteorites	HED (Howardites, Eucrites, and Diogenites) meteorites come from the rocky mantles of asteroids and planets that have separated into mantle and core, and then broken up. These approximate what the density of Earth's mantle would be without gravitational squeezing.

*HED stands for the names of three types of meteorites: howardites, eucrites, and diogenites.

Table 22.2 Finding the fraction of volume that is core

Description	**Earth**	**Mars**	**Venus**	**Mercury**
Planet density (uncompressed) in g/cm^3	4.05	3.74	4.00	5.30
Percent core ((planet density − 3.25 g/cm^3) ÷ 4.75 g/cm^3) × 100	**16.8%**			

Step 2.

Once we have the percent of core, we can use it to find the volume of the core for each planet. The core volume is the percent of core times the volume of the planet. Use the planet volumes in Table 22.3 to calculate the core volume. Record your answers.

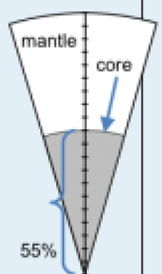
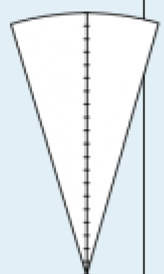
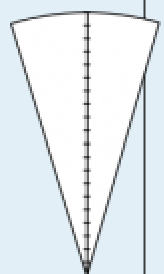
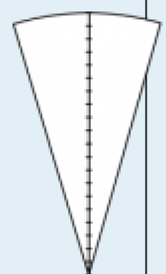
Table 22.3 Finding the volume of the core for each planet

Description	**Earth**	**Mars**	**Venus**	**Mercury**
Planet volume* in km^3	1.47×10^{12}	1.72×10^{11}	1.22×10^{12}	6.23×10^{10}
Core volume in in km^3 (% core ÷ 100) × planet volume	**2.48×10^{11}**			

*Unsqueezed values

Step 3. We can get the radius of the core from its volume by using the formula for the volume of a sphere (volume = $4 \div 3pr^3$, where *r* is the radius). This calculation is done for you in Table 22.4. From these values, express each radius as a percentage of the total radius. To do this, divide the core radius by the planet radius and multiply by 100. Using your results, fill in the diagrams at the bottom of Table 22.4 by drawing in the boundary between the core and mantle.

Table 22.4 Finding the percent of each planet's radius that is core

Description	**Earth**	**Mars**	**Venus**	**Mercury**
Core radius* in km	3,900	1,617	3,581	1,858
Planet radius* in km	7,059	3,447	6,623	2,458
Percent of radius that is core: (core radius ÷ planet radius) × 100	**55%**			
Planet diagram Diagrams represent a wedge of the planet from surface to centre. The distance between each tick mark is 5% of the radius.				

One of the terrestrial planets is thought to have been involved in collisions that resulted in the permanent loss of a substantial amount of its mantle. You might be able to guess which one it is from the uncompressed densities of the planets. It should also be clear from your diagrams. Which planet is it?

See Appendix 3 for Exercise 22.1 answers.

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22.4 Earth's First 2 Billion Years

Karla Panchuk

If you were to get into a time machine and visit Earth shortly after it formed (around 4.5 billion years ago), you would probably regret it. Large patches of Earth's surface would still be molten, which would make landing your time machine very dangerous indeed. If you happened to have one of the newer time-machine models with hovering capabilities and heat shields, you would still face the inconvenience of having nothing to breathe but a tenuous wisp of hydrogen and helium gas, and depending on how much volcanic activity was going on, volcanic gases such as water vapour and carbon dioxide. Some ammonia and methane might be thrown in just to make it interesting, but there would be no oxygen. Assuming you had the foresight to purchase the artificial atmosphere upgrade for your time machine, it would all be for naught if you materialized just in time to see an asteroid, or worse yet another planet, bearing down on your position. The moral of the story is that early Earth was a nasty place, and a time machine purchase is not something to take lightly.

Why was early Earth so nasty?

The early Earth was hot

Chapter 9 explains that Earth's heat comes from the decay of radioactive elements within Earth, as well as from processes associated with Earth's formation. Let's look more closely at how those formation processes heated up Earth:

- Heat came from the thermal energy already contained within the objects that accreted to form the Earth.
- Heat came from collisions. When objects hit Earth, some of the energy from their motion went into deforming Earth, and some of it was transformed into heat. Clap your hands vigorously to experience this on a much smaller (and safer!) scale.
- As Earth became larger, its gravitational force became stronger. This increased Earth's ability to draw objects to it, but it also caused the material making Earth to be compressed, rather like Earth giving itself a giant gravitational hug. Compression causes materials to heat up.

Heating had a very important consequence for Earth's structure. As Earth grew, it collected a mixture of silicate mineral grains as well as iron and nickel. These materials were scattered throughout Earth. That changed when Earth began to heat up: it got so hot that both the silicate minerals and the metals melted. The metal melt was much denser than the silicate mineral melt, so the metal melt sank to Earth's centre to become its core, and the silicate melt rose upward to become Earth's crust and mantle. In other words, Earth unmixed itself. The separation of silicate minerals and metals into a rocky outer layer and a metallic core, respectively, is called **differentiation**. The movement of silicate and metal melts within Earth caused it to heat up even more.

Earth's high temperature early in its history also means that early tectonic processes were accelerated compared to today, and Earth's surface was more geologically active.

Earth was heavily bombarded by objects from space

Although Earth had swept up a substantial amount of the material in its orbit as it was accreting, unrest within the solar system caused by changes in the orbits of Saturn and Jupiter was still sending many large objects on cataclysmic collision courses with Earth. The energy from these collisions repeatedly melted and even vaporized minerals in the crust, and blasted gases out of Earth's atmosphere. Very old scars from these collisions are still detectable, although we have to look carefully to see them. For example, the oldest impact site discovered is the 3 billion year old Maniitsoq "crater" in west Greenland, although there is no crater to see. What is visible are rocks that were 20 km to 25 km below Earth's surface at the time of the impact, but which nevertheless display evidence of deformation that could only be produced by intense, sudden shock.

The evidence of the very worst collision that Earth experienced is not subtle at all. In fact, you have probably looked directly at it hundreds of times already, perhaps without realizing what it is. That collision was with a planet named Theia, which was approximately the size of Mars (Figure 22.4.1). Not long after Earth formed, Theia struck Earth. When Theia slammed into Earth, Theia's metal core merged with Earth's core, and debris from the outer silicate layers was cast into space, forming a ring of rubble around Earth. The material within the ring coalesced into a new body in orbit around Earth, giving us our moon. Remarkably, the debris may have coalesced in 10 years or fewer! This scenario for the formation of the moon is called the **giant impact hypothesis.**

Earth's atmosphere as we know it took a long time to develop

Earth's first experiment with having an atmosphere didn't go well. It started out with a thin veil of hydrogen and helium gases that came with the material it accreted. However, hydrogen and helium are very light gases, and they bled off into space.

Earth's second experiment with having an atmosphere went much better. Volcanic eruptions built up the atmosphere by releasing gases. The most common volcanic gases are water vapour and carbon dioxide (CO_2), but volcanoes release a wide variety of gases. Other important contributions include sulphur dioxide (SO_2), carbon monoxide (CO), hydrogen sulphide (H_2S), hydrogen gas, and methane (CH_4). Meteorites and comets also brought substantial amounts of water and nitrogen to Earth. It is not clear what the exact composition of the atmosphere was after Earth's second experiment, but carbon dioxide, water vapour, and nitrogen were likely the three most abundant components.

One thing we can say for sure about Earth's second experiment is that there was effectively no free oxygen (O_2, the form of oxygen that we breathe) in the atmosphere. We know this in part because prior to 2 billion years ago, there were no sedimentary beds stained red from oxidized iron minerals. Iron minerals were present, but not in oxidized form. At that time, O_2 was produced in the atmosphere when the Sun's ultraviolet rays split water molecules apart; however, chemical reactions removed the oxygen as quickly as it was produced.

Figure 22.4.1 Artist's impression of a collision between planets. A similar collision between Earth and the planet Theia might have given us our Moon. Fortunately for us, the collision that gave us the moon was a glancing blow rather than the direct hit shown here. Earth might not have survived a direct hit.

It wasn't until well into Earth's third experiment—life—that the atmosphere began to become oxygenated. Photosynthetic organisms used the abundant CO_2 in the atmosphere to manufacture their food, and released O_2 as a by-product. At first all of the oxygen was consumed by chemical reactions, but eventually the organisms released so much O_2 that it overwhelmed the chemical reactions and oxygen began to accumulate in the atmosphere, although present levels of 21% oxygen didn't occur until about 350 Ma. Today the part of our atmosphere that isn't oxygen consists largely of nitrogen (78%).

The oxygen-rich atmosphere on our planet is life's signature. If geologic process were the only processes controlling our atmosphere, it would consist mostly of carbon dioxide, like the atmosphere of Venus. It is an interesting notion (or a disconcerting one, depending on your point of view) that for the last 2 billion years the light reflected from our planet has been beaming a bar code out to the universe, similar to the ones in Figure 22.1.4, except ours says "oxygen." For 2 billion years, our planet has been sending out a signal that could cause an observer from another world to say, "That's odd… I wonder what's going on over there."

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- Figure 22.4.1: "Planetary Smash-Up" by NASA/JPL-Caltech. Public domain.

22.5 Are There Other Earths?

Karla Panchuk

If by that you mean, are there other planets where we could walk out of a spaceship with no equipment other than a picnic basket, and enjoy a pleasant afternoon on a grassy slope near a stream, then that remains to be seen. On the other hand, if you are asking if other planets exist that are rocky worlds approximately Earth's size, and orbiting within their star's **habitable zone** (the zone in which liquid water, and potentially life, can exist), then many planet hunters are cautiously optimistic that we have found at least 12 such worlds so far.

As of July 2015, NASA's Kepler mission has detected a total of 4,696 possible exoplanets. The Kepler spacecraft has an instrument to measure the brightness of stars, and looks for tiny variations in brightness that could be caused by a planet passing between the star it orbits and the instrument observing the star. Potential candidates are then examined in more detail to see whether they are in fact planets or not. So far 1,030 of those candidates have been confirmed as planets.[1] Of those, 12 satisfy the criteria of being one to two times the size of Earth, and orbiting their star within the habitable zone.[2]

The uncertainty about the 12 possible Earth-like worlds is related to their composition. We don't yet know their composition; however, it is tempting to conclude that they are rocky because they are similar in size to Earth. Remember the rules of the accretion game: you can only begin to collect gas once you are a certain size, and how much matter you collect depends on how far away from the Sun you are. Given how large our gas giant and ice giant planets are compared to Earth, and how far away they are from the Sun, we would expect that a planet similar in size to Earth, and a similar distance from its star, should be rocky.

It isn't quite as simple as that, however. We are finding that the rules to the accretion game can result in planetary systems very different from our own, leading some people to wonder whether those planetary systems are strange, or ours is, and if ours is strange, how strange is it?

Consider that in the Kepler mission's observations thus far, it is very common to find planetary systems with planets larger than Earth orbiting closer to their star than Mercury does to the Sun. It is rare for planetary systems to have planets as large as Jupiter, and where large planets do exist, they are much closer to their star than Jupiter is to the Sun. To summarize, we need to be cautious about drawing conclusions from our own solar system, just in case we are basing those conclusions on something truly unusual.

On the other hand, the seemingly unique features of our solar system would make planetary systems like ours difficult to spot. Small planets are harder to detect because they block less of a star's light than larger planets. Larger planets farther from a star are difficult to spot because they don't go past the star as frequently. For example, Jupiter goes around the Sun once every 12 years, which means that if someone were observing our solar system, they might have to watch for 12 years to see Jupiter go past the Sun once. For Saturn, they might have to watch for 30 years.

So let's say the habitable-zone exoplanets are terrestrial. Does that mean we

1. You can access a catalogue of confirmed exoplanets found by NASA and other planet-hunting organizations at http://exoplanet.eu/catalog/
2. Read more about habitable-zone planets discovered so far at http://www.nasa.gov/jpl/finding-another-earth

could live there?

The operational definition of "other Earths," which involves a terrestrial composition, a size constraint of one to two times that of Earth, and location within a star's habitable zone, does not preclude worlds incapable of supporting life as we know it. By those criteria, Venus is an "other Earth," albeit right on the edge of the habitable zone for our Sun. Venus is much too hot for us, with a constant surface temperature of 465°C (lead melts at 327°C). Its atmosphere is almost entirely carbon dioxide, and the atmospheric pressure at its surface is 92 times higher than on Earth. Any liquid water on its surface boiled off long ago. Yet the characteristics that make Venus a terrible picnic destination aren't entirely things we could predict from its distance from the sun. They depend in part on the geochemical evolution of Venus, and at one time Venus might have been a lot more like a youthful Earth. These are the kinds of things we won't know about until we can look carefully at the atmospheres and compositions of habitable-zone exoplanets.

Exercise 22.2 How well do we know the size of exoplanets?

One of the techniques for finding exoplanets is to measure changes in the brightness of a host star as the planet crosses in front of it and blocks some of its light. This diagram shows how the brightness changes over time. The dip in brightness reflects a planet crossing between the star and the instrument observing the star.

Often the planet itself is too small to see directly. If all we know is how the planet affects the brightness of the star, and we can't even see the planet, then how do we know how big the planet is? The answer is that the two are related. We can write an equation for this relationship using the radius of the planet and the radius of the star.

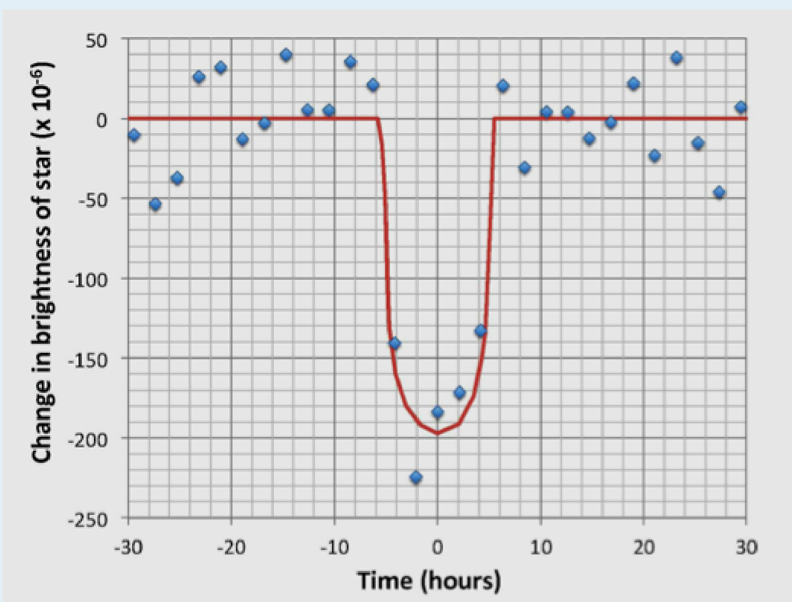

Figure 22.5.1 Plot showing how the star Kepler-452 dims as the planet Kepler-452b moves in front of it.

$$\text{decrease in brightness} = \frac{\text{planet radius}^2}{\text{star radius}^2}$$

Equation 1: Calculate decrease in brightness

Let's try this out for the Earth-like exoplanet called Kepler-452b. The first thing we need to know is the size of the host star Kepler-452. We can get that information by comparing its surface temperature and brightness to that of the sun. Start by calculating the ratios of the sun's temperature to the star's temperature, and the star's luminosity to the sun's luminosity using the data in Table 22.5. Record your answers in the table. Then find the star's radius using the following equation, and record your result:

$$\text{star radius} = \text{sun radius} \times \left(\frac{\text{sun temperature}}{\text{star temperature}}\right)^2 \times \sqrt{\frac{\text{star luminosity}}{\text{sun luminosity}}}$$

Equation 2: Calculate star radius. [Image Description]

Table 22.5 Calculating the radius of star Kepler-452

Description	Sun	Kepler-452	Ratio
Temperature (degrees Kelvin)	5,778	5,757	
Luminosity (× 1026 watts)	3.846	4.615	
Radius (km)	696,300		

The second thing we need to know is how the brightness of Kepler-452 changes as planet Kepler-452b moves in front of it. Use the plot shown in this exercise box to find this information. Find the value on the y-axis where the red curve shows the most dimming from the planet and record your result in Table 22.6.

Table 22.6 Calculating the radius of planet Kepler-452b

Decrease in brightness*	Earth radius in km	Kepler-452b radius in km	Kepler-452b radius/Earth radius
x 10^{-6}	6,378		

* Because we know this is a decrease, you don't need to keep the negative sign.

Use the following equation to find the radius of Kepler-452b:

$$\text{planet radius} = \sqrt{\text{star radius}^2 \times \text{decrease in brightness}}$$

Equation 3: Calculate planet radius.

To put the size of Kepler-452b in perspective, divide its radius by that of Earth and record your answer.

See Appendix 3 for Exercise 22.2 answers.

Image Descriptions

Equation 2 image description: Star radius equals sun radius times begin fraction sun temperature over star temperature end fraction squared times begin square root begin fraction star luminosity over sun luminosity end fraction end square root. [Return to Equation 2]

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- Figure 22.5.1: © Karla Panchuk. CC BY. Based on data from Jenkins, J. et al, 2015, Discovery and validation of Kepler-452b: a 1.6REarth super Earth exoplanet in the habitable zone of a G2 star, Astronomical Journal, V 150, DOI 10.1088/0004-6256/150/2/56.

Summary

Karla Panchuk

The topics covered in this chapter can be summarized as follows:

Section	Summary
22.1 Starting with a Big Bang	The universe began 13.77 billion years ago when energy, matter, and space expanded from a single point. Evidence for the big bang is the cosmic "afterglow" from when the universe was still very dense, and red-shifted light from distant galaxies, which tell us the universe is still expanding.
22.2 Forming Planets from the Remnants of Exploding Stars	The big bang produced hydrogen, helium, and lithium, but heavier elements come from nuclear fusion reactions in stars. Large stars make elements such as silicon, iron, and magnesium, which are important in forming terrestrial planets. Large stars explode as supernovae and scatter the elements into space.
22.3 How to Build a Solar System	Solar systems begin with the collapse of a cloud of gas and dust. Material drawn to the centre forms a star, and the remainder forms a disk around the star. Material within the disk clumps together to form planets. In our solar system, rocky planets are closer to the Sun, and ice and gas giants are farther away. This is because temperatures near the Sun were too high for ice to form, but silicate minerals and metals could solidify.
22.4 Earth's First 2 Billion Years	Early Earth was heated by radioactive decay, collisions with bodies from space, and gravitational compression. Heating melted Earth, causing molten metal to sink to Earth's centre and form a core, and silicate melt to float to the surface and form the mantle and crust. A collision with a planet the size of Mars knocked debris into orbit around Earth, and the debris coalesced into the moon. Earth's atmosphere is the result of volcanic degassing, contributions by comets and meteorites, and photosynthesis.
22.5 Are There Other Earths?	The search for exoplanets has identified 12 planets that are similar in size to Earth and within the habitable zone of their stars. These are thought to be rocky worlds like Earth, but the compositions of these planets are not known for certain.

Questions for Review

Answers to review questions can be found in Appendix 2.

1. How can astronomers view events that happened in the universe's distant past?

2. In this image of three spectra, one is from the Sun, and the other two are from galaxies. One of the galaxies is the Andromeda galaxy. Which spectrum is from Andromeda?

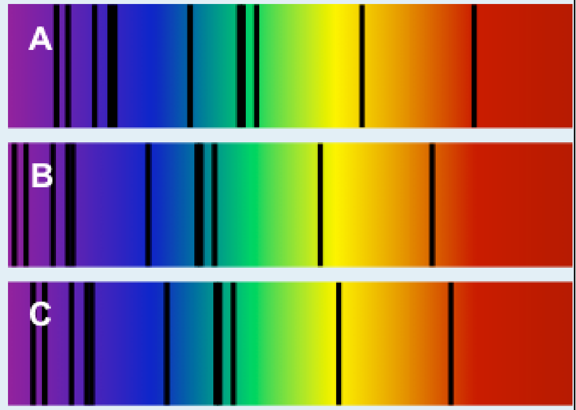

Figure A Spectra for the sun and two galaxies.

3. Astronomers looking for some of the earliest stars in the universe were surprised to find a planetary system called HIP 11952, which existed 12.8 billion years ago. This was very early in the universe's history, when stars still consisted largely of hydrogen and helium. Do you think there were terrestrial planets in this system? Why or why not?
4. Summarize the trends in size and composition of objects in the solar system.
5. What is the frost line, and what does it help to explain?
6. This cartoon shows three of the same type of solar system object. One goes on an adventure and comes back the worse for wear. What are the objects, and where might they be located?

Figure B Denizens of the solar system.

7. Why is Pluto not considered a planet?
8. What is differentiation, and what must happen to a planet or asteroid for differentiation to occur?
9. The exoplanet Kepler-452b is within the habitable zone of its star. In our solar system, planets a similar distance from the Sun are terrestrial planets. Why can we not say for certain that Kepler-452b's distance from its star means it is a terrestrial planet?
10. Of the planetary systems discovered thus far, none are exactly like our solar system. Does this mean our solar system is unique in the universe?

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