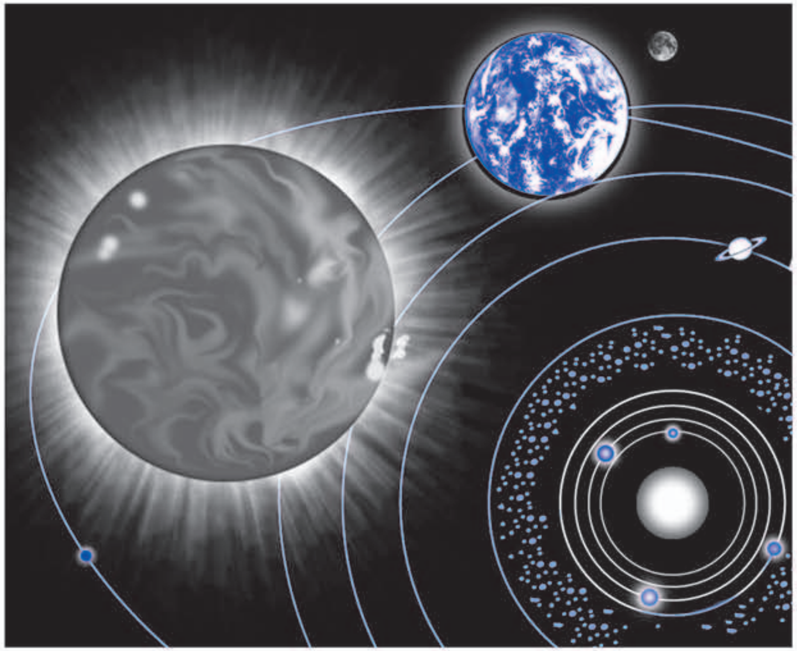


Introduction to

Earth and Space Science

Tom Hsu, Ph.D.

FIRST EDITION
CPO Science
Peabody, Massachusetts 01960

Unit 1: Energy in the Earth System

Unit 2: Earth Science

Unit 3: Astronomy

UNIT 3

Astronomy

Chapter 9

The Universe

Introduction to Chapter 9

So far in this unit, you have learned mostly about objects that are relatively close to Earth such as other planets, their moons, and the sun. The solar system occupies a very tiny portion of the Milky Way Galaxy. This galaxy contains hundreds of billions of stars like the sun, and is one of many billions of galaxies in the universe. The universe is a term astronomers use to describe everything that exists including all matter and energy. In this chapter, you will learn about objects that are very far away including stars and galaxies. You will also read about how many scientists believe the universe began.

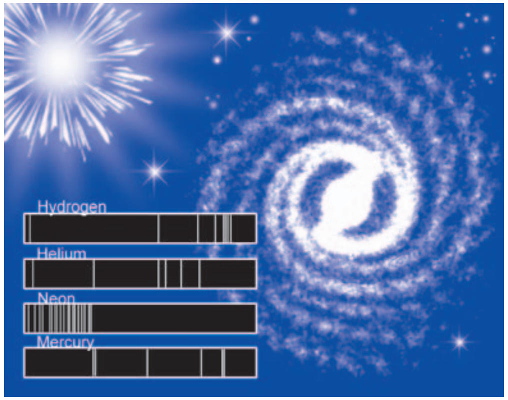
Investigations for Chapter 9

9.1	**Stars**	*What are stars made of?*

Astronomers use a spectrometer to analyze the light emitted by stars and determine the elements from which stars are composed. In this Investigation, you will use a spectrometer to analyze light and examine spectral diagrams to determine the composition and temperature of stars.

9.2	**Galaxies and the Universe**	*How do we use light to measure the distances to stars and galaxies?*

Distances to stars and galaxies in the universe are so vast that they are very difficult to measure. One of the tools astronomers use to measure distances in the universe is light. In this Investigation, you will discover the mathematical relationship between how bright an object appears from a distance, and how much light it actually gives off. This important relationship is used by astronomers to calculate distances in the universe.



Learning Goals

In this chapter, you will:

- Identify the conditions necessary for fusion to occur inside a star.
- Describe the information that spectroscopy provides about stars.
- Relate the color of a star to its temperature.
- Explain the factors that determine the brightness of a star in the sky.
- Discuss the importance of the H-R diagram to astronomers.
- Explain the relationship between mass and the life cycle of a star.
- Describe the phases in the life cycle of a sun-like star.
- Discuss how the death of a massive star is responsible for the creation of elements heavier than helium on the periodic table.
- Describe how the composition and size of planets is related to their formation and proximity to the sun.
- Identify the structure of the Milky Way Galaxy and the location of our solar system within the galaxy.
- Explain how astronomers measure the distance to stars and galaxies.
- Identify the scientific evidence that supports the Big Bang theory.

Vocabulary

absolute brightness
apparent brightness
Big Bang
Cepheid
constellation
Doppler shift
H-R diagram
inverse square law
main sequence stars
nebula
parallax
planetary system
protostar
spectroscopy
standard candle
supernova

9.2 Galaxies and the Universe

Early civilizations believed that Earth was the center of the universe. In the 16th century, we became aware that Earth is a small planet orbiting a medium-sized star. It was only in the 20th century that we became aware that the sun is one of billions of stars in the Milky Way Galaxy, and that there are billions of other galaxies in the universe. In the past three decades, astronomers have found evidence that the universe is expanding and that it originated 10 to 20 billion years ago. In this section you will learn about galaxies and theories about how the universe began. You will also learn how astronomers measure the vast distances of galaxies and stars from Earth.

What is a galaxy?

The discovery of other galaxies

A *galaxy* is a huge group of stars, dust, gas, and other objects bound together by gravitational forces. In the 1920s, American astronomer Edwin Hubble (1889-1953) discovered that there were galaxies beyond the Milky Way. He used a new, 2.5-meter reflecting telescope to establish that some of the many fuzzy patches of light long known to astronomers were indeed separate galaxies. For example, when he focused the huge telescope on an object thought to be a nebula in the constellation Andromeda, Hubble could see that the “nebula” actually consisted of faint, distant stars. He named the object the Andromeda Galaxy. Just since Hubble’s time, astronomers have discovered a large number of galaxies. In fact, many new galaxies are detected each year using the telescope named after Hubble—the Hubble Space Telescope or HST.

Galaxy shapes

Astronomers classify galaxies according to their shape. *Spiral galaxies* like the Milky Way consist of a central, dense area surrounded by spiraling arms. *Elliptical galaxies* look like the central portion of a spiral galaxy without the arms. *Lenticular galaxies* are lens-shaped with a smooth, even distribution of stars and no central, denser area. *Irregular galaxies* exhibit peculiar shapes and do not appear to rotate like those galaxies of other shapes. Figure 9.12 shows an example of each galaxy shape. The Cartwheel Galaxy (Figure 9.13) demonstrates what happens when two galaxies collide. This shape occurred when a large, spiral galaxy was struck by a smaller galaxy. The ring-like band of stars formed much like ripples occur when a rock is dropped into water.

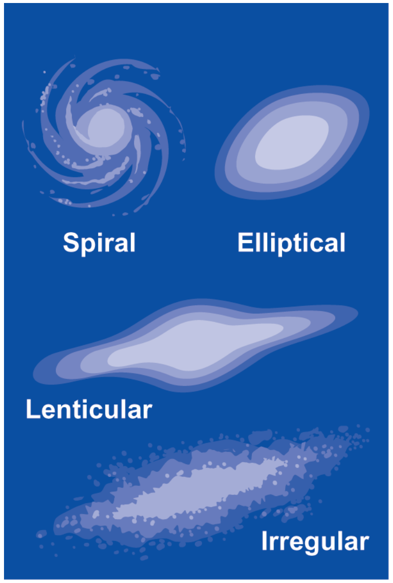


Figure 9.12: *Galaxy shapes.*

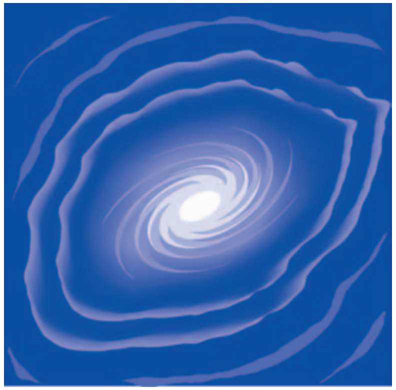


Figure 9.13: *When the Cartwheel Galaxy was struck by a smaller galaxy, a ring-like band of stars formed, much like ripples form in a pond.*

The Milky Way Galaxy

Structure of our galaxy

The sun, along with an estimated 200 billion other stars, belongs to the Milky Way Galaxy. The Milky Way is a typical spiral galaxy. From above, it would look like a giant pinwheel, with arms radiating out from a central region. The stars are arranged in a *disk* that is more than 100,000 light years across. If you could look at it from the side, you would see that our galaxy is much flatter than it is wide. In fact, it is only about 3,000 light years thick on average. At the center of the disk is a denser region of stars called the *nuclear bulge*. Surrounding the outer regions of the galaxy is an area containing clusters of older stars known as the *halo*.
Figure 9.14 shows a diagram of the Milky Way Galaxy.

The disk

The disk of the Milky Way is a flattened, rotating system that contains young to middle-aged stars, along with gas and dust. The sun sits about 26,000 light years from the center of the disk and revolves around the center of the galaxy about once every 250 million years. When you look up at the night sky, you are actually looking through the disk of the galaxy. On a very clear night, you can see a faint band of light stretching across the sky. This is the combined light of billions of stars in the disk of our galaxy, so numerous that their light merges together.

The center of the galaxy

Since we are located in the outer part of the galaxy, the *interstellar* (between the stars) dust blocks out much of the visible light coming from objects within the disk. Because of this, astronomers use infrared and radio telescopes to study our galaxy. Using these tools, they have learned that the center of the galaxy is crowded with older stars and hot dust. Recent studies have suggested that a black hole, with a mass of more than a million suns, exists at the very center of the galaxy. It is believed that this black hole has enough gravitational pull to keep in orbit all of the stars, gas, and dust in the Milky Way Galaxy.

Evidence for the black hole theory

The evidence for a huge black hole comes from measurements of the orbital speeds of stars and gas at the center of the galaxy. In one study, an infrared telescope was used to measure the orbital speeds of 20 stars over a three-year period. It was determined that these stars were orbiting at speeds of up to 1,000 kilometers per second (3 million miles per hour!). This extremely high orbital speed requires an object with a mass that is over 2 million times that of the sun.

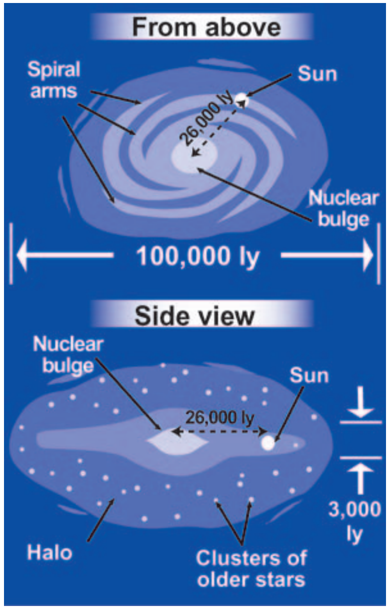


Figure 9.14: *The Milky Way is a typical spiral galaxy.*

The Local Group

The Milky Way is part of a cluster of galaxies known as the Local Group. In addition to our galaxy, the group contains other spiral galaxies such as the Andromeda Galaxy. Irregular galaxies in the Local Group include the Large and Small Magellanic Clouds. In all, there are about 40 galaxies in the Local Group. Other groups of galaxies also exist.

Determining distances to closer objects in the universe

Measuring the distance of closer stars

One of the greatest challenges facing astronomers is how to determine the vast distances of stars and galaxies from Earth. This information is key to mapping the universe. For objects that are under 1,000 light years from Earth, astronomers use a method called **parallax**. Parallax is the apparent change in position of an object when you look at it from different directions.

An illustration of parallax

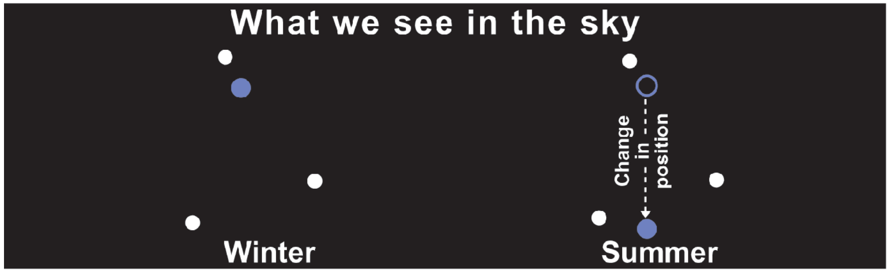
To illustrate parallax, hold one finger about six inches from your nose. Close your left eye and look at your finger with your right eye. Next, close your right eye and look at your finger with your left eye. Because your eyes are in different positions, your finger appears to move. The same is true of stars in the sky. As Earth revolves around the sun, the stars appear to change positions in the sky over the course of one year. It is actually Earth that is changing position as it revolves around the sun, while the stars remain fixed in the background (Figure 9.15).

Parallax only works for closer stars

Parallax only works for stars that are relatively close because as distance from Earth increases, the change in angle of a star becomes less measurable. You can demonstrate this by looking at a finger held before your nose as you did before. This time, try moving your finger farther and farther away from your nose while looking at it with each eye. You will notice that the farther away it is, the smaller the movement appears to become until you can detect no movement at all.

How to measure distance using parallax

To use parallax, astronomers determine the position of a star in the sky in relation to other stars that are too far away to show movement. Next, they look at the star six months later—when Earth is on the opposite side of the sun, and measure its change in position in relation to the faraway stars. Using geometry, they can determine the distance of the star from Earth (Figure 9.16 and below).



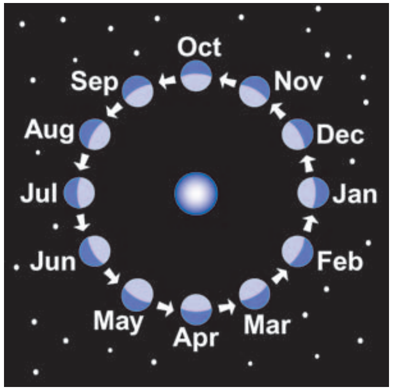


Figure 9.15: *The night side of Earth always faces away from the sun. As Earth revolves around the sun, the stars seen in the sky appear to move even though they remain fixed.*

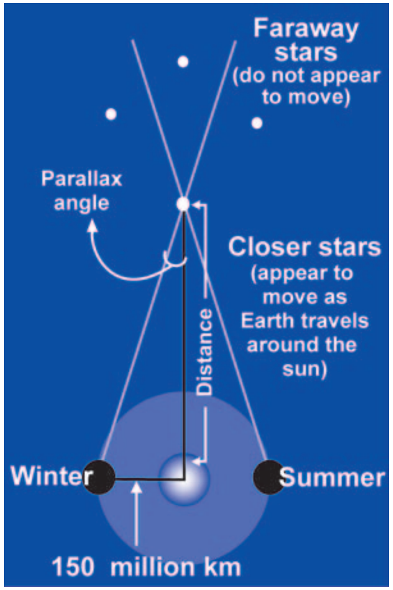


Figure 9.16: *Using parallax to measure the distance to a star.*

Measuring distances to faraway objects in the universe

The inverse square law

Light is very important to astronomers in measuring the distances to objects that are more than 1,000 light years away. Recall that the apparent brightness of an object depends on how far away it is, and how much light it actually gives off (its absolute brightness). The mathematical relationship between these variables is known as the inverse square law and is used to determine the distance to stars and galaxies.

Inverse square law

$$\text{Apparent brightness} \rightarrow B = \frac{\overset{\text{Absolute brightness}}{L}}{\underbrace{4\pi}_{\text{Constant }(4 \times 3.14)}\underset{\text{Distance}}{D^2}}$$

Apparent brightness vs. distance

$$B \, \alpha \, \frac{1}{D^2}$$

The inverse square law shows how the apparent brightness of an object decreases as you move away from it. The amount of decrease in apparent brightness can be quantified using the formula at left. The symbol α indicates a proportional relationship. For example, if you are looking at a candle from one meter away, and then you move two meters away, its apparent brightness will decrease by a factor of *four*. Or if you move three meters away, its apparent brightness will decrease by a factor of *nine*. By what factor will its apparent brightness decrease if you move 10 meters away? If you did an experiment where you measured the apparent brightness of a candle at various distances, starting at one meter, your graph would look similar to Figure 9.17.

Solving for distance

$$D = \sqrt{\frac{L}{4\pi B}}$$

The inverse square law is important to astronomers because if they know the apparent and absolute brightness of an object, they can determine its distance by rearranging the variables to solve for D as shown in the equation at left.

Recall that apparent brightness (B) can be easily measured using a photometer. The challenge facing astromomers is how to determine the absolute brightness (L) of faraway objects.

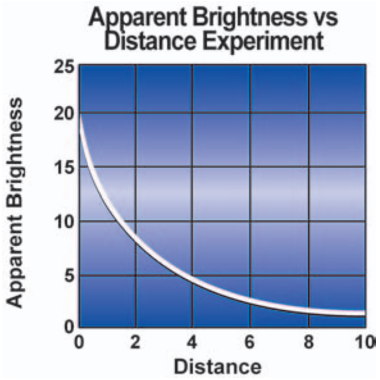


Figure 9.17: *A graph of the apparent brightness of a candle at various distances.*

Measuring brightness

Brightness is measured in units of power. In the laboratory, you can measure the brightness of a light source in *watts*. Because the brightness of objects in space is so great, astronomers developed *solar luminosity units*. One solar luminosity unit is equal to the brightness of the sun, or about 3.9×10^{26} watts. This is comparable to the combined brightness of 400 trillion trillion 100-watt light bulbs! Our galaxy emits as much light as 1.0×10^{10} suns.

Standard candles

Astronomers have found a way to *infer* values for absolute brightness (*L*) using a source of light called a **standard candle**. A standard candle is an object, such as a star, whose absolute brightness is known.

Measuring the distance to stars in the Milky Way

You are already familiar with one type of standard candle called *main sequence stars*. Recall that main sequence stars are found in a diagonal band on the H-R diagram. It is estimated that 90 percent of all stars are main sequence. Through observation, astronomers can determine if a star is a main sequence star by comparing it to stars on the H-R diagram. By determining the unknown star's temperature (using a spectrometer), they can infer its absolute brightness by choosing a similar main sequence star on the H-R diagram as shown in Figure 9.18. Next, they measure the unknown star's apparent brightness, and use the inverse square law to calculate its distance. Astronomers use this method to measure distances to stars in the Milky Way and nearby galaxies—out to distances of about 200,000 light years. Beyond that, astronomers cannot see main sequence stars and must rely on other types of standard candles.

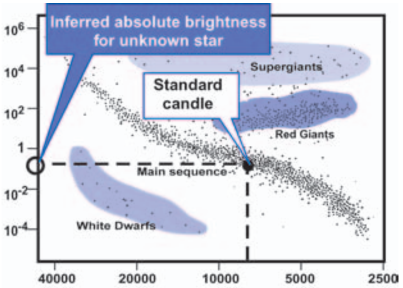


Figure 9.18: *Inferring the absolute brightness of an unknown star using the H-R diagram and main sequence stars as a standard candle.*

Measuring distances to galaxies

A second type of standard candle is called a **Cepheid** star. This type of star was discovered by Henrietta Leavitt (1868-1921), an American, in the early 1900s. Cepheid stars "pulsate" in regular periods ranging from a few days to a few weeks. Leavitt discovered that there is a relationship between the period of Cepheid star and its absolute brightness. This meant that by measuring the period of a Cepheid star, astronomers could determine its absolute brightness and then, use the inverse square law to calculate its distance. Astronomers locate Cepheids in faraway galaxies and use them to map distances between galaxies in the universe. The Hubble Space Telescope actively searches for Cepheids in faraway galaxies.

Going even farther

Beyond 100 million light years, Cepheid stars are too faint to observe—even with the Hubble. For these distances, astronomers must rely on a third type of standard candle—a certain type of supernova. By observing the rate at which light from the supernova fades after the initial explosion, astronomers can use a mathematical formula to determine its absolute brightness, and then use the inverse square law to infer the distance to the galaxy in which the supernova resides.

The North Star

The North Star is the brightest Cepheid star. Because it is only 390 light years from Earth, its distance can also be measured using parallax. This is one of the stars that helped astronomers refine the use of Cepheids to determine distances. The Cepheid star first discoverd, Delta Cephei, is also relatively close to Earth at 300 light years.

The Big Bang theory

What is the Big Bang theory?

The *universe* is defined as everything that exists, including all matter and energy. While there are many theories about how it began, the one that has gained credibility among scientists is called the Big Bang. The Big Bang theory states that the universe began as a huge explosion that occurred somewhere between 10 and 20 billion years ago.

The explosion

According to the Big Bang theory, all of the matter and energy in the universe started out compressed into a space no bigger than the nucleus of an atom. Suddenly, a huge explosion occurred that sent everything that makes up the universe out in all directions. For an instant, the universe was an extremely hot ball of fire that began to expand rapidly. Extreme heat from the explosion (10 billion°C) caused the formation of subatomic particles.

Formation of hydrogen and helium

Immediately after the explosion, the universe began to expand and cool. Some scientists believe that it expanded from the size of an atomic nucleus, to 6×10^{30} kilometers in a fraction of a second! In less than a second, the expansion of the universe started to slow down. The universe became a cloud of matter and energy that was rapidly cooling and becoming less dense as it expanded. After a few minutes, at temperatures of around 1 billion°C, hydrogen nuclei began forming. Next, hydrogen nuclei began combining in pairs to form helium nuclei.

Radiation period

Ten thousand years after the explosion, most of the energy in the universe was in the form of electromagnetic radiation of different wavelengths including X rays, radio waves, and ultraviolet radiation. As the universe continued to cool and expand, these waves were changed into a form called *cosmic microwave background radiation* which can be measured today.

The first galaxies

After 300,000 years, the temperature had cooled to around 10,000°C. Lithium atoms began to form at this stage and electrons joined with the atomic nuclei to form the first stable (neutral) atoms. The universe continued as a giant cloud of gas until about 300 million years after the Big Bang. Parts of the gas cloud began to collapse and ignite to form clusters of stars—the first galaxies. The universe has continued to form galaxies since then. These galaxies continue to expand outward from the initial point of the Big Bang.

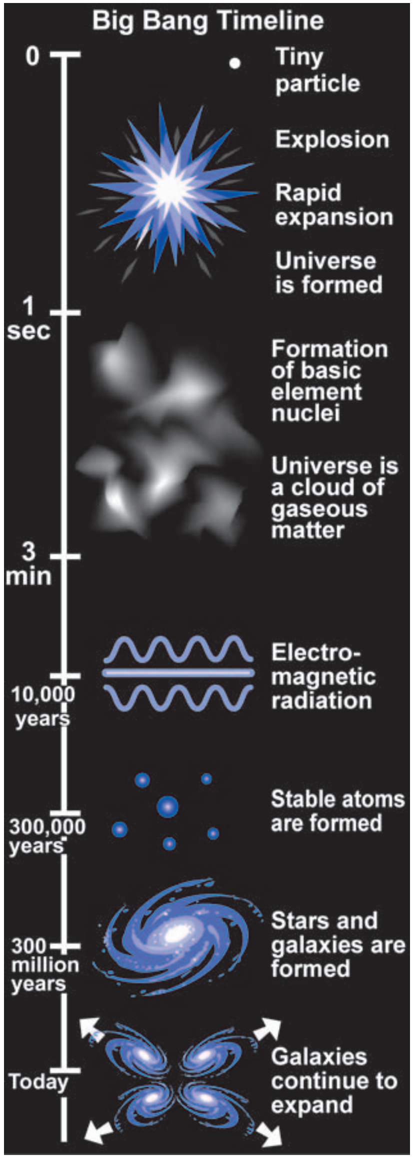


Figure 9.19: *A timeline for the Big Bang.*

Evidence for the Big Bang

Growing evidence

When it was first introduced, not everyone believed the Big Bang. In fact, the name "Big Bang" was made up by scientists to mock the theory. Unfortunately for them, the name stuck! As with any new theory, the Big Bang became more accepted as new scientific tools and discoveries established supporting evidence. In particular, scientific understanding of electromagnetic waves such as visible light, X rays, and microwaves, has provided important evidence for supporting the Big Bang theory.

Doppler shift

In the 1800s, Christian Doppler (1803-53), an Austrian physicist, discovered that when the source of a sound wave is moving, its frequency changes. You may have noticed this effect if you have heard a car drive by with its horn blaring. As the car approaches, you hear the horn playing high "notes," and as the car passes, you hear the horn shift to lower notes as the car moves farther away. The change in sound you hear is caused by a **Doppler shift** (also called the Doppler effect).

How does it work?

As the car is moving toward you, the sound waves are compressed relative to where you are standing. This shortens the wavelength and causes the frequency to increase (recall that wavelength and frequency are inversely related). As the car moves away, the sound waves are stretched out, causing longer wavelengths and lower frequencies (Figure 9.20). The sound of the horn changes as the car passes by because the sound waves are being compressed and then stretched. If you could measure the rate of change in the frequency, you could measure the speed of the car.

Doppler shift and electromagnetic waves

Doppler shift also occurs with electromagnetic waves such as visible light, X rays, and microwaves. This phenomenon is an important tool used by astronomers to study the motion of objects in space. For example, if an object is moving toward Earth, the light waves it emits are compressed, shifting them toward the violet end (shorter wavelengths, higher frequencies) of the visible spectrum. If an object is moving away from Earth, the light waves it emits are stretched, shifting them toward the red end (longer wavelengths, lower frequencies) of the visible spectrum (Figure 9.21).

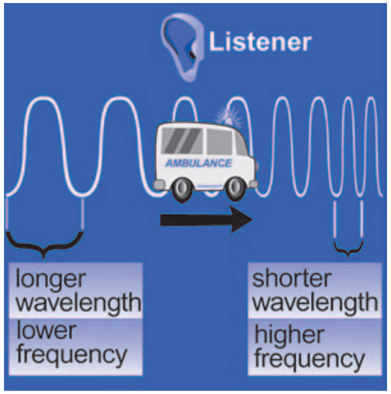


Figure 9.20: *The Doppler effect occurs when an object is moving toward or away from an observer.*

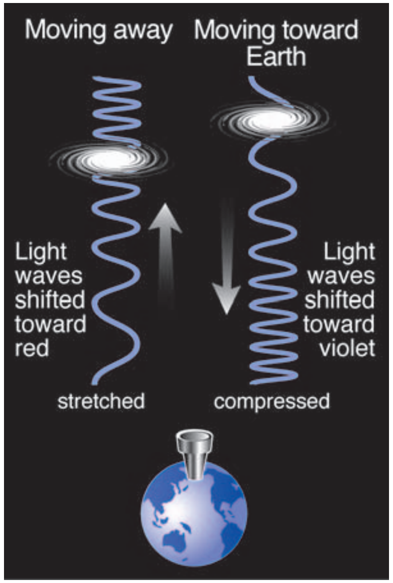


Figure 9.21: *Doppler shift is used to study the motion of objects in space.*

Sirius is moving away from Earth

In the 1890s, astronomers began to combine the use of spectroscopy and Doppler shift to study the motion of stars and other objects in space. One of the first stars they studied, Sirius, had spectral lines in the same pattern as the spectrum for hydrogen. However, these lines did not have the exact same measurements as those for hydrogen. Instead, they were shifted toward the red end of the visible spectrum. Scientists realized that this meant that Sirius was moving away from Earth. They could even determine how fast Sirius was moving away by measuring the amount that the lines had shifted toward red (Figure 9.22).

Evidence for the Big Bang

In the early 1900s, Hubble began to study the motion of galaxies. He used Cepheid stars to determine the distances of galaxies from Earth. Next, he studied the Doppler shift of each galaxy and found that the farther away a galaxy was, the faster it was moving. He was also able to determine the direction that each galaxy was moving. By the early 1930s, he had enough evidence to prove that galaxies were moving away from a single point in the universe. This supported two key parts of the Big Bang Theory: that the universe is expanding and that it originated from a single point.

Microwave background radiation

In the 1960s, Arno Penzias and Robert Wilson, two American astrophysicists, were trying to measure electromagnetic radiation emitted by the Milky Way. No matter how they refined their technique, they kept detecting a background noise that interfered with their observations. This noise seemed to be coming from all directions and had little variation in frequency. After publishing a paper describing their failed experiment, it was determined that they had discovered the cosmic microwave background radiation predicted by the Big Bang theory. Penzias and Wilson won the Nobel Prize for their discovery.

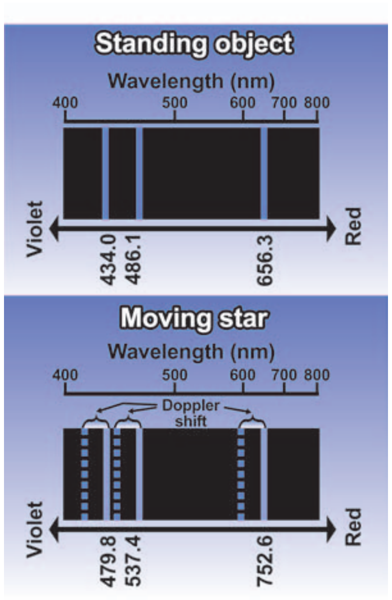


Figure 9.22: *The top diagram shows the wavelength of hydrogen spectral lines for an object that is not moving. The bottom diagram shows the hydrogen spectral lines for a moving star. While the lines are in the exact same pattern, the values for wavelength have shifted toward the red end of the spectrum. Astronomers can determine how fast the object is moving away by calculating the amount of shift that has occurred.*

Dramatic is a good word to describe both this cover and the study of Earth and space science. The cover is a universal-scale palette of what you will find in this text. On the front, we witness Earth's interior and see magnetic field lines radiating from the core. Following the magnetic field lines to the back cover, you will encounter the arcing solar prominences on the sun's fiery surface. Central in our solar system, the sun provides a source of energy that drives our weather, seasons, ocean currents, and food synthesis as long as there is water to cycle from place to place. Water moves on the cover in the images of a brewing storm, global cloud patterns, and the curl of an ocean wave reaching shore. In the deeper blues of the cover are images of nebulae, the birthplace of stars. Not surprisingly the nebula on the back cover is called the Horsehead Nebula. In striking contrast with the drama that unfolds on Earth, we have our moon, a familiar "face" in the sky. Earth's surface has changed again and again over its long history due to the powerful and slow movement of tectonic plates and the relatively fast effects of water and wind. The moon does not experience plate tectonics. It, therefore, remains unchanged and an excellent "lab" to study ancient rocks and land formations. With today's technology, we can see billions of years into the past and bring astronomically distant regions of the universe closer to us. We at CPO Science with Bruce Holloway, the spirited illustrator of the cover, hope these images will bring you closer to the wonders of Earth and space science and scientific discovery.

The CPO Science Development Team

Introduction to Earth and Space Science

ISBN 1-58892-063-1
1 2 3 4 5 6 7 8 9 - QWE - 05 04 03

CPO Science
26 Howley Street
Peabody, MA 01960
(800) 932-5227
http://www. cpo.com

Printed and Bound in the United States of America