Chapter 17
Galaxies and the Universe

How big is *everything*? How long is *forever*? In science, *everything* means the universe including all matter and energy. In science, forever means the amount of time the universe exists or will exist. As a start to answering these deep questions, think about the night sky. It's dark. But why is the night sky dark? Imagine the universe was infinite, stretching off to forever in all directions. That means in any direction you looked, you would eventually see a star. If there were stars in every possible direction, the night sky should be light, not dark. This puzzled people for a long time and became known as Olber's Paradox.

The solution to Olber's Paradox is that the universe is not infinite in all directions, but has a finite size. Nor is the universe forever. Time had a beginning between 10 billion and 20 billion years ago and time may or may not have an end. It is amazing where you find yourself as you try to understand something so simple as why the night sky is dark. Of course, we are not sure all our answers are correct. Read ahead about galaxies and the universe. What do *you* think?

Key Questions

1. ***How is the universe organized?***
2. ***Did the universe have a beginning? Does it have an end?***
3. ***How can science answer questions like these?***

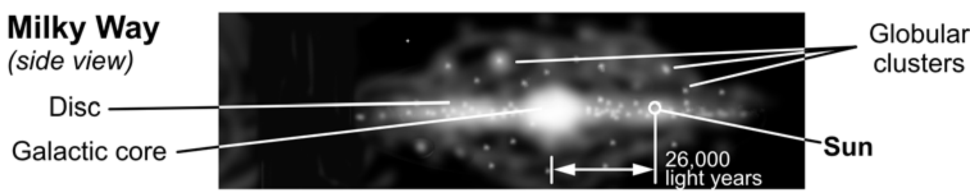
17.1 Galaxies

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-size 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 50 years, astronomers have found evidence that the universe is expanding and that it originated 10 billion to 20 billion years ago. In this section you will learn about galaxies and theories about how the universe began.

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. The sun, along with an estimated 200 billion other stars, belongs to the **Milky Way galaxy**. The Milky Way is a typical *spiral galaxy* (Figure 17.1). From above, it would look like a giant pinwheel, with arms radiating out from the center. Although some stars are in *globular clusters* above and below the main disk, the majority are arranged in a disk that is more than 100,000 light years across and only 3,000 light years thick.



Our sun is 26,000 light years from the center

The disk of the Milky Way is a flattened, rotating system that contains young to middle-aged stars, along with gas and dust (Figure 17.2). 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 looking through that disk of the galaxy. On a crystal 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 galaxy, so numerous that their light merges.

VOCABULARY

galaxy - a group of stars, dust, gas, and other objects held together by gravitational forces.

Milky Way galaxy - the spiral galaxy to which our solar system belongs.

Figure 17.1: *The Whirlpool galaxy is a typical spiral, like the Milky Way.*

Figure 17.2: *How the Milky Way appears in the night sky. We are looking in from the edge of the disk.*

Types of galaxies

The discovery of other galaxies

At the turn of the 20th century astronomers believed the Milky Way galaxy *was* the entire universe. As telescopes got better, though, some "smudges" that were thought to be nebulae in the Milky Way were recognized to be whole galaxies far outside our own. The discovery was made in the 1920s by Edwin Hubble, an American astronomer. When he focused a 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 (1889-1953), astronomers have discovered a large number of galaxies. In fact, many galaxies are detected each year using the famous telescope launched into orbit in 1990: 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. *Barred spiral* galaxies have a bar-shaped structure in the center. *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 17.3 shows examples of some galaxy shapes.

Galaxies change shape over time

The shapes of galaxies change over time. It is impossible to actually see the changes in a single galaxy, since it takes hundreds of millions of years. However, by looking at many galaxies, astronomers can see similar galaxies at different times in their histories. This observational data has allowed astronomers to develop computer based models which calculate how a galaxy changes over hundreds of millions of years. It is now believed that the barred spiral form is just one phase of a regular spiral. Computer simulations show how the "bar" forms and disappears repeatedly as a spiral galaxy rotates.

Figure 17.3: *Some representative galaxy shapes.*

Distances between galaxies

Galaxies are a million times farther away than stars

The distances between stars are 10,000 times greater than the distances between planets. *The distances between galaxies are a million times greater than the distances between stars*. For example, the distance from Earth to the nearest star is 4.3 light years, but from Earth to the Whirlpool galaxy is over 30 million light years.

The local group of galaxies

The Milky Way belongs to a group of about 30 galaxies called the local group. This group includes the Large Magellanic Cloud (179,000 light years) and the Small Magellanic Cloud (210,000 ly). These Magellanic Clouds are small, irregular galaxies of less than 100,000 stars. The local group also includes Andromeda, an elliptical galaxy 2.9 million light years away (Figure 17.4).

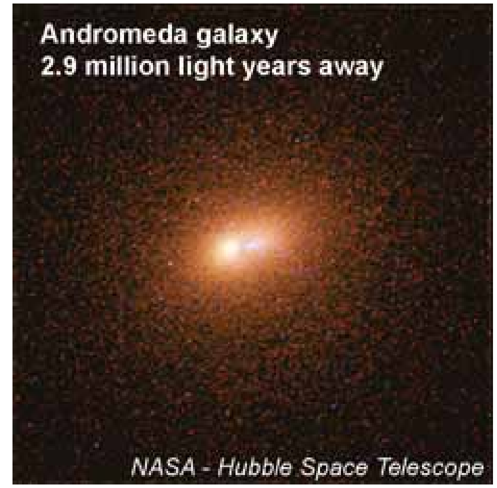


Figure 17.4: *The Andromeda galaxy is an elliptical galaxy in our local group.*

Galactic collisions

Galaxies move through space singly and in groups. Galaxies even collide with each other in slow dances of stars that take millions of years to complete (Figure 17.5)

Figure 17.5: *Two galaxies that are near to colliding.*

Determining the distance to nearby galaxies

Figuring out the distance between galaxies is one of the more difficult tasks in astronomy. A faint (low brightness) object in the night sky could be a dim object that is relatively nearby or a bright object that is far, far away. The most reliable method for estimating the distance to a galaxy is to find a star whose luminosity is known. If the luminosity is known, the inverse square law can be used to find the distance from the observed brightness.

Distant galaxies

This method works for the closest galaxies. However, the vast majority of galaxies are too far away to see single stars even with the best telescopes. Beyond 150 million light years, astronomers compare size and type with closer galaxies to estimate the luminosity of the farther ones. This method is not as accurate and, consequently, the distances to far galaxies are known only to within a factor of two.

The central black hole

The center of the galaxy

Since we are located in the outer part of the galaxy, dust between the stars blocks out much of the visible light coming from objects in the disk. Because of this, astronomers use infrared and radio telescopes to study our galaxy. 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.

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.

Relativity predicts black holes

One of the strangest predictions of Einstein's theory of relativity is the existence of *black holes*. To understand a black hole, consider throwing a ball fast enough to leave the Earth completely. If the ball does not go fast enough, the Earth's gravity eventually pulls it back. The minimum speed an unpowered projectile must have to escape the planet's gravity is called the *escape velocity*. The stronger gravity becomes, the higher the escape velocity.

The escape velocity of a black hole

If gravity becomes strong enough, the escape velocity can reach the speed of light. A *black hole* is an object with such strong gravity that its escape velocity equals or exceeds the speed of light. When the escape velocity equals the speed of light, nothing can get out because nothing can go faster than light. In fact, even light cannot get out, because in general relativity, light is affected by gravity. The name *black hole* comes from the fact that anything that falls in never comes out. Since no light can get out, the object is "black" (Figure 17.7). To make a black hole, a very large mass must be squeezed into a relatively tiny space. For example, to make the Earth into a black hole, you would have to squeeze the mass of the entire planet down to the size of your thumb.

Figure 17.6: *The core of the Milky Way is in the direction of the constellation Sagittarius. Astronomers believe a huge black hole lives at the core of the Milky Way and most other large galaxies.*

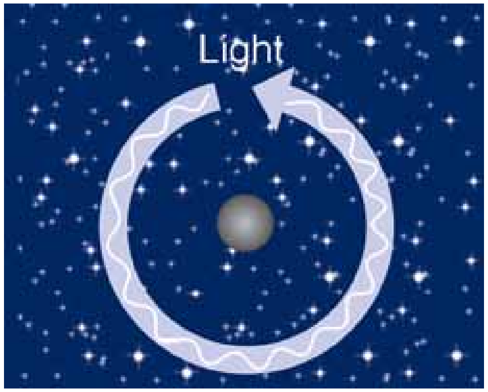


Figure 17.7: *Light from a black hole cannot escape because the escape velocity is higher than the speed of light.*

The expanding universe

Sirius is moving away from Earth

In the 1890s, astronomers began to use spectroscopy to study the 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. This was a puzzle at first, until scientists realized that a red-shifted spectrum meant 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 17.8).

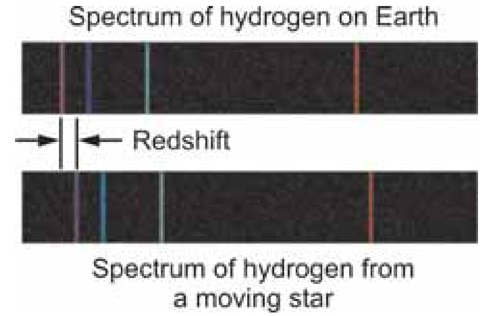


Figure 17.8: *The top diagram shows the hydrogen spectrum for an object that is not moving. The bottom diagram shows the hydrogen spectral lines for a moving star. While the lines are in the exact same pattern, they have shifted toward the red end of the spectrum.*

Redshift

Redshift is caused by relative motion that increases the distance from the source to the observer. The faster the source of light is moving away from the observer, the greater the redshift. The opposite (blueshift) happens when an object is moving toward the observer. A star moving toward Earth would show a spectrum for hydrogen that was shifted toward the blue end of the scale.

Discovery of the expanding universe

In the late 1920s, Hubble began to measure the distance and redshift of galaxies. Much to his surprise, he discovered that the farther away a galaxy was, the faster it was moving away from Earth. By the early 1930s, he had enough evidence to prove that galaxies were moving away from each other with a speed proportional to the distance between them. This concept came to be known as the *expanding universe*.

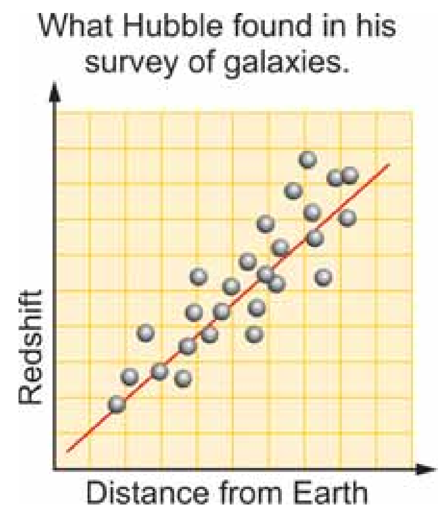


Figure 17.9: *Hubble discovered that the redshift (speed) of galaxies increased proportionally to their distance.*

The Big Bang theory

The expanding universe was a great surprise to scientists. Before Hubble's discovery, people believed the universe had existed in its same form for all time. The fact that the universe was expanding implies the universe must have been smaller in the past than it is today. In fact, it implies that the universe must have had a *beginning*. Astronomers today believe the universe exploded outward from a single point smaller than an atom into the vast expanse of galaxies and space we see today. This idea is known as the Big Bang theory.

The Big Bang theory

The Big Bang theory

The **Big Bang** theory says the universe began as a huge explosion between 10 billion and 20 billion years ago. According to this theory, all matter and energy started in a space smaller than the nucleus of an atom. Suddenly, (no one knows why) a huge explosion occurred that sent everything that makes up the universe spraying out in all directions. In its first moments of existence, the universe was an extremely hot fireball of pure energy that began to expand rapidly.

Protons and neutrons form at 4 minutes

As the universe expanded, it cooled down as its energy spread out over a larger volume. About four minutes after the Big Bang, the universe had cooled enough that protons and neutrons could stick together to form the nuclei of atoms. Because atoms were still flying around with high energy, heavy nuclei were smashed apart. Only one helium atom survived for every 12 hydrogen atoms. Almost no elements heavier than helium survived. When we look at the matter in the universe today, we see this ratio of hydrogen to helium left by the Big Bang, with the exception of elements formed later in stars.

Matter and light decouple in 700,000 years

For the next 700,000 years the universe was like the inside of a star: hot ionized hydrogen and helium. At the age of 700,000 years, the universe had expanded enough to become transparent to light. At this point, the light from the fireball was freed from constant interaction with hot matter. The light continued to expand separately from matter and became the cosmic background radiation we see today.

Stars and galaxies form

When the universe was about 1 billion years old, it had expanded and cooled enough that galaxies and stars could form. At this point the universe probably began to look similar to how it looks today. The sun and solar system formed about 4 billion years ago, by which time the universe was 12 billion years old.

Unresolved questions

While scientists feel relatively confident about the overall picture, they are not confident about the details. For example, recent observations suggest the expansion of the universe is accelerating. This is a puzzle because, if anything, gravity should be slowing the expansion down.

VOCABULARY

Big Bang - theory that the universe began as a huge explosion 10 billion to 20 billion years ago.

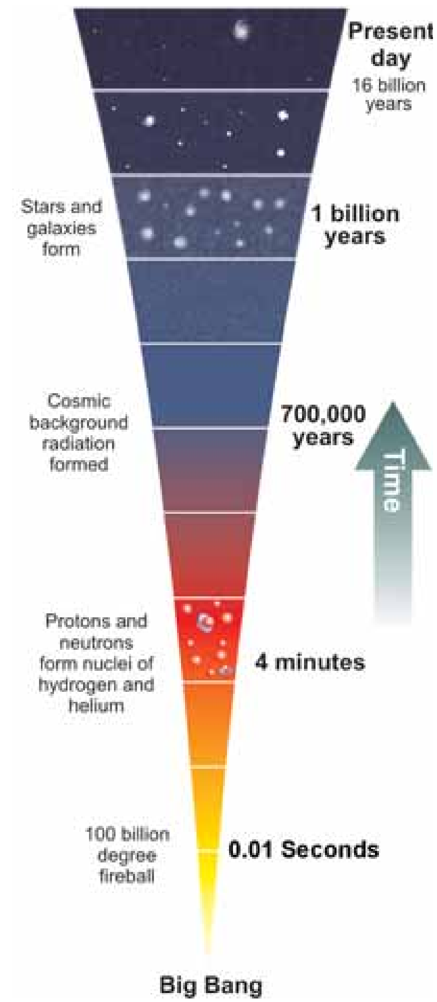


Figure 17.10: *Big Bang timeline.*

Evidence for the Big Bang theory

Evidence for the Big Bang

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 more evidence.

The fact that galaxies are expanding away from each other is a strong argument for the Big Bang. As far as we can look into the universe, we find galaxies are expanding away from each other. On average, we do not see galaxies coming toward each other (Figure 17.11).

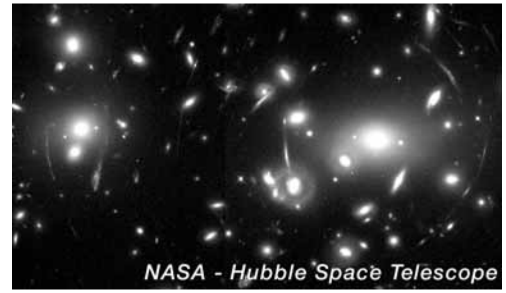


Figure 17.11: *The observed expansion of the universe is strong evidence for the Big Bang theory.*

Microwave background radiation

In the 1960s, Arno Penzias and Robert Wilson, two American astrophysicists, were trying to measure electromagnetic waves given off 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.

When you light a match, the flame bursts rapidly from the first spark and then cools as it expands. When the Big Bang exploded, it also created hot radiation. This radiation has been expanding and cooling for 16 billion years. The radiation is now at a temperature only 2.7°C above absolute zero and it fills the universe. The *cosmic background radiation* is the "smoke" from the Big Bang that fills the room (that is, the universe), even 16 billion years later. The "noise" that Penzias and Wilson found was the cosmic microwave background radiation predicted by the Big Bang theory (Figure 17.12).

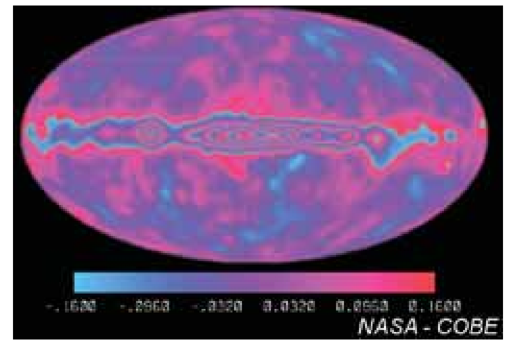


Figure 17.12: *The COBE satellite measured this image of the cosmic background radiation. (NASA)*

Ratios of the elements

We have other evidence that supports the Big Bang theory. The proportion of hydrogen to helium is consistent with the physics of the Big Bang (Figure 17.13). Elements heavier than hydrogen and helium are formed in stars. When stars reach the end of their life cycles, they spread heavy elements such as carbon, oxygen, and iron out into the universe. If the universe were significantly older, there would be more heavy elements present compared with hydrogen and helium.

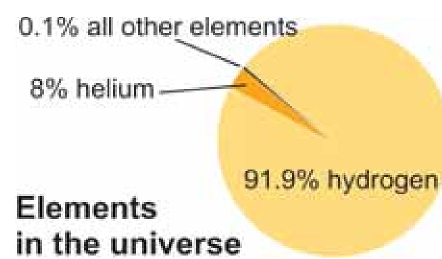


Figure 17.13: *The universe is mostly hydrogen with a small amount of helium and tiny amounts of other elements.*

17.1 Section Review

1. Which is bigger, a supergiant star or a galaxy?
2. In which galaxy do we live?
3. The number of stars in our home galaxy is closest to:
   a. 200.
   b. 200,000.
   c. 200,000,000.
   d. 200 billion.
4. What two important discoveries are credited to astronomer Edwin Hubble?
5. List four galaxy shapes.
6. The distances between galaxies are in the range of:
   a. 100 kilometers.
   b. 100 light years.
   c. 1 million light years.
   d. 1 billion light years.
7. How do astronomers estimate the distance between galaxies?
8. What do scientists believe is at the center of the Milky Way galaxy?
9. Why does a black hole appear black?
10. How did astronomers discover that the star Sirius was moving away from Earth?
11. What did Hubble discover about the relationship between a galaxy's location and speed?
12. According to the Big Bang theory, how large was the universe before it exploded and expanded in all directions?
13. How many years did it take for stars to begin to form after the Big Bang?
14. What evidence for the Big Bang did the scientists Arno Penzias and Robert Wilson discover?

CHALLENGE

When reading about black holes, you learned that Earth would have to be squeezed into the size of a marble one centimeter in diameter to make its gravity strong enough to be a black hole.

Use what you learned about density in Chapter 4 to calculate how dense Earth would be if it were compressed to this size. Compare your calculated density to that of common materials such as lead and steel..

ASTRONOMY CONNECTION

A Spectacular Show of Lights

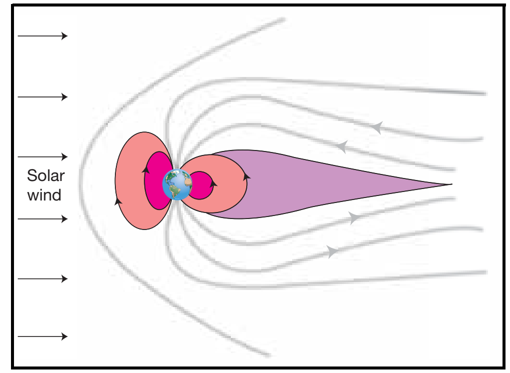
Do you think of weather as an Earth-only phenomenon? Then it will broaden your horizons to know there is weather in outer space, and, just like on Earth, conditions there change constantly.

Weather on our planet is affected by factors such as temperature, wind, precipitation, and by the sun's heat and light. In space, the sun drives the weather. Explosions on the sun's surface can cause radiation storms, changes in magnetic fields, and movement of energetic particles. The fast-moving solar wind carries charged particles away from the sun. Some of these particles and energy are able to penetrate Earth's upper atmosphere, and when this happens, an aurora is created - a spectacular show of lights.

Photo - collection of Dr. Herbert Kroehl, NGDC, NOAA

Charged particles and auroras

Our planet is a magnetic object. Magnetic field lines travel between the north and south poles. Charged electron particles trapped in these field lines create what is known as Earth's magnetic field (also called the magnetosphere).



This magnetosphere protects Earth from solar wind that contains energetic particles and radiation. An aurora is caused by energy from the sun. Charged particles from the sun travel down Earth's magnetic field lines forming oval shapes. These so-called auroral ovals cover each magnetic pole. When electrons hit Earth's upper atmosphere, light particles are released. These colliding solar particles and atmospheric gases create aurora lights.

Generally, aurorae occur at higher latitudes, closer to the magnetic poles. Auroral ovals are usually located at 60° and 70° latitude, north and south. At 45°, aurorae are seen about fives times per year. Above 55°, aurorae are visible almost every night if viewing conditions are right. In November 2004, auroral ovals could be seen as far south as Arizona, whose latitude is 31° to 37°.

Dazzling details

An aurora looks like streaks of colored light in the dark night sky. Commonly seen aurora colors include green, yellow, and red. The gases present in the atmosphere determine the color. The electromagnetic radiation in an aurora also includes infrared and ultraviolet, neither of which the human eye can see.

The aurora in the Northern Hemisphere is called aurora borealis or the northern lights, and is popularly viewed from Alaska, Canada, Iceland, Scandinavia, and Russia. In the Southern Hemisphere, the southern lights, or aurora australis, tend to occur in remote, barely populated areas.

This photo of aurora australis was taken at the Antarctica South Pole Weather Station in 1979.

Clear, dark nights are best for seeing an aurora. Cloud cover, moonlight, and city lights can interfere with viewing.

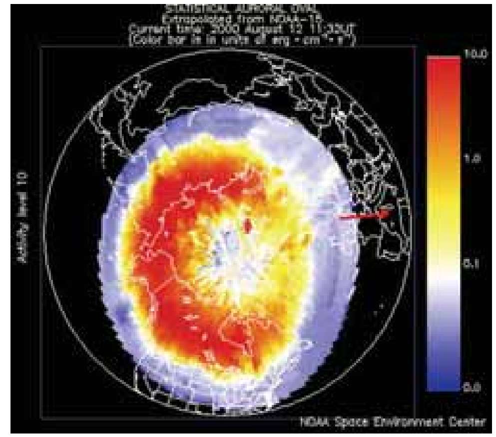
Space Environment Center

The National Oceanic & Atmospheric Administration (NOAA) and the Air Force operate the Space Environment Center (SEC) in Boulder, Colo. The center provides real-time information about solar events and space weather that may affect people and equipment. It issues alerts and warnings to any organization that needs space weather information.

Space weather storms can damage satellites, interrupt cell phone systems, and disable electric power grids, which are networks of power lines and equipment that provide electrical power to large areas. In 1989, Montreal, Quebec, lost power for nine hours because of a large geomagnetic storm.

Space weather can also affect short wave radio systems and Global Positioning Systems (GPS). GPS is a satellite system that tracks the location of vehicles, planes, and boats. GPS relies on accurate and timely data that can be hampered severely by geomagnetic storms. NASA also requires timely information to make decisions about launching satellites and manned space vehicles.

NOAA's Polar Orbiting Environmental Satellites (POES) contain monitors and detectors that gather data as they travel over the poles. POES provides information about aurora size, intensity, and location. The SEC website supplies regularly updated auroral oval images and data.



The SEC uses magnetometers to measure geomagnetic activity. Data is provided to create indices or guides to determine the likelihood of an aurora. The K index provides data on a scale from 0 to 9. The higher the value the more likely an aurora will occur. The Kp index (also on a 0-9 scale) is updated every three hours and collects data from 13 geomagnetic observatories. These values tell how far south an aurora can be seen past the magnetic north pole.

Maybe some night your location, viewing conditions, and the geomagnetic activity all will be right for you to witness a spectacular natural show of lights.

Questions:

1. What causes an aurora?
2. What is the SEC and what is its role?
3. What conditions are needed for viewing an aurora?

Chapter 17 Assessment

Vocabulary

Select the correct term to complete the sentences.

galaxy	Big Bang theory

1. Our solar system is located in the Milky Way ____.
2. The ____ explains how the universe began.

Concepts

1. Name and describe the four shapes used to classify galaxies.
2. To which galaxy does our sun belong and what shape does our galaxy take?
3. Describe the Milky Way galaxy. Refer to:
   a. the position of our sun,
   b. its dimensions in light years, and
   c. the location of a black hole.
4. What is the Big Bang theory?
5. Describe three pieces of evidence that support the Big Bang theory.
6. According to the Big Bang theory, how old is the universe?
7. As observed from Earth, the light from a distant star is shifted toward the red end of the visible spectrum. What would this indicate to an astronomer?
8. Everything that exists, including all matter and energy, is known as the:
   a. solar system.
   b. galaxy.
   c. universe.
9. In the 1920's, Edwin Hubble measured that the further away a galaxy was, the more redshift it had. What was the significance of this increased redshift?
10. It is believed that the universe is:
    a. expanding.
    b. shrinking.
    c. not changing.
11. Where and when was the helium found in the sun formed?
12. Where were the elements carbon, oxygen, and iron formed?
13. A black hole is:
    a. a hole in the universe that is black in color.
    b. the black regions of space you can see between stars.
    c. an object with such strong gravity that nothing can escape it.
14. Why can't light escape from a black hole?

Problems

1. Rank the following from smallest to largest in mass:
   a. Milky Way galaxy
   b. our sun
   c. the universe
   d. Earth
   e. the black hole at the center of the Milky Way Galaxy.
2. Rank the following from closest to farthest away from Earth:
   a. Andromeda galaxy
   b. our sun
   c. the moon
   d. the star, Sirius