MPS Physics 2
Supplemental Text

The Universe, Space, and Stars

This chapter is intended to supplement the Conceptual Physics text for the Physics 2 course.

A special thanks to MPS teachers Jim Stock, Matt Jagusch, and Kate Rosok for their forward thinking and efforts in compiling this resource.

We wish to thank CK-12 for help with this material:
http://www.ck12.org/saythanks

Opening image courtesy of NASA and European Space Agency.
http://en.wikipedia.org/wiki/File:Messier51_sRGB.jpg. Public Domain.

This chapter of MPS Physics 2 Supplemental Text supports the state standards related to the universe.

<u>MPS Learning Targets for Physics 2:</u>

8.6 I can use evidence to explain the leading theories for the formation of the universe, stars, and our solar system. (9.3.3.2.1, 9.3.3.3.1, 9.3.3.3.2, 9.1.1.1.6, 9.1.1.1.7)
8.11 I can explain how the rules of the universe can be discovered, and the implication that those rules are the same everywhere. (9.1.1.1.1)

Topic	**Supporting Target**
Accessing student knowledge about the universe	I can describe the relationships between the various structures of the universe.
Describing the theory for the formation of the solar system	I can describe how the solar system formed.
Describing the life cycle of stars	I can explain the lifecycle of stars and describe the evidence supporting this model.
Evaluating theories of cosmology	I can construct an explanation of the Big Bang theory based on astronomical evidence.
Relating the theory of the Standard Model	I can explain how the rules of the Universe can be discovered, and the implication that those rules are the same everywhere.

Minnesota state standards 9.3.3.2.1 through 9.3.3.3.2.

The Universe
A.The solar system, sun, and Earth formed over billions of years.
9.3.3.2.1 Describe how the solar system formed from a nebular cloud of dust and gas 4.6 billion years ago.
B.The big bang theory states that the universe expanded from a hot, dense chaotic mass, after which chemical elements formed and clumped together to eventually form stars and galaxies.
9.3.3.3.1 Explain how evidence, including the Doppler shift of light from distant stars and cosmic background radiation, is used to understand the composition, early history and expansion of the universe.
9.3.3.3.2 Explain how gravitational clumping leads to nuclear fusion, producing energy and the chemical elements of a star.

Contents

Section 1 <u>Stars</u>

Supporting Learning Target:

I can explain the lifecycle of stars and describe the evidence supporting this model.

Vocabulary

- asterism
- black hole
- main sequence star
- neutron star
- nuclear fusion reaction
- luminosity
- parallax
- red giant
- star
- supernova
- white dwarf

1.1 Introduction

When you look at the sky on a clear night, you can see dozens, perhaps even hundreds, of tiny points of light. Almost every one of these points of light is a **star**, a giant ball of glowing gas at a very, very high temperature. Stars differ in size, temperature, and age, but they all appear to be made up of the same elements and to behave according to the same principles. Stars do not "burn"; instead they release light, both heat and sunlight, by the process of fusion.

1.2 Constellations

People of many different cultures, including the Greeks, identified patterns of stars in the sky. We call these patterns constellations. The **Figure** below shows one of the most easily recognized constellations.

*This **asterism** is visible in the evening sky from January to March, so the Ojibwe, or Anishinabe, called it the wintermaker or the Giant. The ancient Greeks thought this group of stars looked like a hunter, so they named it Orion after their mythical hunter. The line of three stars at the center is "Orion's Belt".*

Why do the patterns in constellations and in groups or clusters of stars, called **asterisms**, stay the same night after night? Although the stars move across the sky, they stay in the same patterns. This is because the apparent nightly motion of the stars is actually caused by the rotation of Earth on its axis. The patterns also shift in the sky with the seasons as Earth revolves around the Sun. As a result, people in a particular location can see different constellations in the winter than in the summer. For example, in the Northern Hemisphere Orion is a prominent constellation in the winter sky, but not in the summer sky. This is the annual traverse of the constellations.

Check out this *Giizhig Anung Masinaaigan* (Ojibwe Sky Star Map) at http://www.tribalcollegejournal.org/archives/25273 or *Makoce Wicanhpi Wowapi [D(L)akota* Star Map] at http://web.stcloudstate.edu/aslee/. Did you find the wintermaker?

1.3 Apparent Versus Real Distances

Although the stars in a constellation appear close together as we see them in our night sky, they are not at all close together out in space. In the constellation Orion, the stars visible to the naked eye are at distances ranging from just 26 light-years (which is relatively close to Earth) to several thousand light-years away.

Measuring Star Distances

How can you measure the distance of an object that is too far away to measure? Now what if you don't know the size of the object or the size or distance of any other objects like it? That would be very difficult, but that is the problem facing astronomers when they try to measure the distances to stars.

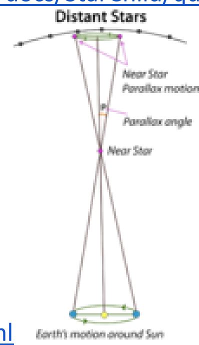
Parallax

Distances to stars that are relatively close to us can be measured using **parallax**. Parallax is an apparent shift in position that takes place when the position of the observer changes.

To see an example of parallax, try holding your finger about 1 foot (30 cm) in front of your eyes. Now, while focusing on your finger, close one eye and then the other. Alternate back and forth between eyes, and pay attention to how your finger appears to move. The shift in position of your finger is an example of parallax. Now try moving your finger closer to your eyes, and repeat the experiment. Do you notice any difference? The closer your finger is to your eyes, the greater the position changes because of parallax.

As the **Figure** below shows, astronomers use this same principle to measure the distance to stars. Instead of a finger, they focus on a star, and instead of switching back and forth between eyes, they switch between the biggest possible differences in observing position. To do this, an astronomer first looks at the star from one position and notes where the star is relative to more distant stars. Now where will the astronomer go to make an observation the greatest possible distance from the first observation? In six months, after Earth moves from one side of its orbit around the Sun to the other side, the astronomer looks at the star again. This time parallax causes the star to appear in a different position relative to more distant stars. From the size of this shift, astronomers can calculate the distance to the star.

For more about parallax, visit http://starchild.gsfc.nasa.gov/docs/StarChild/questions/parallax.html and



http://hyperphysics.phy-astr.gsu.edu/hbase/astro/para.html

Parallax is used to measure the distance to stars that are relatively nearby.

A parallax exercise is seen here: http://www.astro.ubc.ca/~scharein/a311/Sim/new-parallax/Parallax.html.

Other Methods

Even with the most precise instruments available, parallax is too small to measure the distance to stars that are more than a few hundred light years away. For these more distant stars, astronomers must use more indirect methods of determining distance. Most of these methods involve determining how bright the star they are looking at really is. For example, if the star has properties similar to the Sun, then it should be about as bright as the Sun. The astronomer compares the observed brightness to the expected brightness.

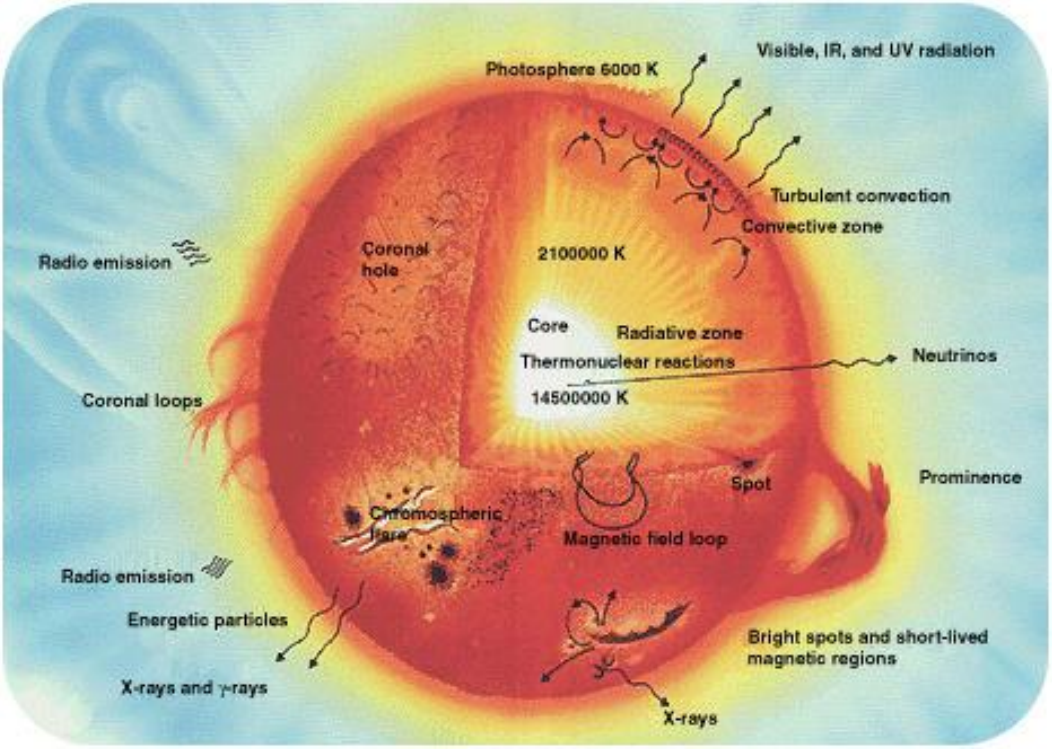
14. Star Power

The Sun is Earth's major source of energy, yet the planet only receives a small portion of all energy released by the sun, and the Sun is just an ordinary star. Many stars which are more massive produce much more energy than the Sun. The energy source for all stars is nuclear fusion.

Nuclear Fusion

Stars are made mostly of hydrogen and helium, which are packed so densely in a star that in the star's center the pressure is great enough to initiate nuclear fusion reactions. In a **nuclear fusion reaction**, the nuclei of atoms combine to create a new atom. Most commonly, in the core of a star, six hydrogen atoms fuse to create one helium atom, two hydrogen atoms, and a lot of energy. (Figure below)
(*Sources*:http://commons.wikimedia.org/wiki/File:FusionintheSun.png License: GNU-FDL)

In a star, the energy from fusion reactions in the core pushes outward to balance the inward pull of gravity. This energy moves outward through the layers of the star until it finally reaches the star's outer surface. The outer layer of the star glows brightly, sending the energy out into space as electromagnetic radiation, including visible light, heat, ultraviolet light, and radio waves (**Figure** below).



A diagram of a star like the Sun.

On Earth, fusion happens in only a few places and only under exceptional conditions. Although nuclear fusion reactions require a lot of energy to get started, once they are going they produce enormous amounts of energy (**Figure** below). We create fusions reaction in thermonuclear bombs and in particle accelerators. We have used fusion as a tool of war, and as a tool to examine the basic physics of our universe.

A thermonuclear bomb is an uncontrolled fusion reaction in which enormous amounts of energy are released.

1.5 How Stars Are Classified

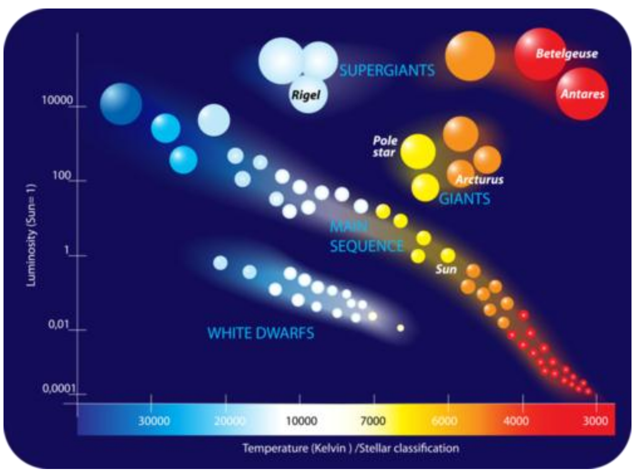
We classify stars based on their **luminosity**, or brightness, and on their color and temperature. The many different colors of stars reflect the star's temperature. In Orion (as shown in the section on asterism above) the bright, red star in the upper left named Betelgeuse (pronounced BET-ul-juice) is not as hot than the blue star in the lower right named Rigel.

Luminosity

From Earth we can see many stars, among them the sun. When we are on the half of the earth facing away from the sun (you know it as night), we see stars at many distances and of many different brightnesses. If we could move all stars so they were a set distance from earth, say 10 light years, then we could compare their absolute brightnesses instead of their apparent brightnesses. This absolute brightness, or luminosity, is one way we classify stars. The more massive a star, the brighter it will be. There is a direct relationship between mass and brightness.

Color and Temperature

Think about how the color of a piece of metal changes with temperature. A coil of an electric stove will start out black but with added heat will start to glow a dull red. With more heat the coil turns a brighter red, then orange. At extremely high temperatures the coil will turn yellow-white, or even blue-white (it's hard to imagine a stove coil getting that hot). A star's color is also determined by the temperature of the star's surface. Relatively cool stars are red, warmer stars are orange or yellow, and extremely hot stars are blue or blue-white (**Figure** below).



A Hertzsprung-Russell diagram shows the brightness and color of main sequence stars. The brightness is indicated by luminosity and is higher up the y-axis. The temperature is given in degrees Kelvin and is higher on the left side of the x-axis. How does our Sun fare in terms of brightness and color compared with other stars?

Classifying Stars by Color

Color is the most common way to classify stars. **Table** below shows the classification system. The class of a star is given by a letter. Each letter corresponds to a color, and also to a range of temperatures. Note that these letters don't match the color names; they are left over from an older system that is no longer used.

Class	Color	Temperature Range	Sample Star
O	Blue	30,000 K or more	Zeta Ophiuchi
B	Blue-white	10,000–30,000 K	Rigel
A	White	7,500–10,000 K	Altair
F	Yellowish-white	6,000–7,500 K	Procyon A
G	Yellow	5,500–6,000 K	Sun
K	Orange	3,500–5,000 K	Epsilon Indi
M	Red	2,000–3,500 K	Betelgeuse, Proxima Centauri

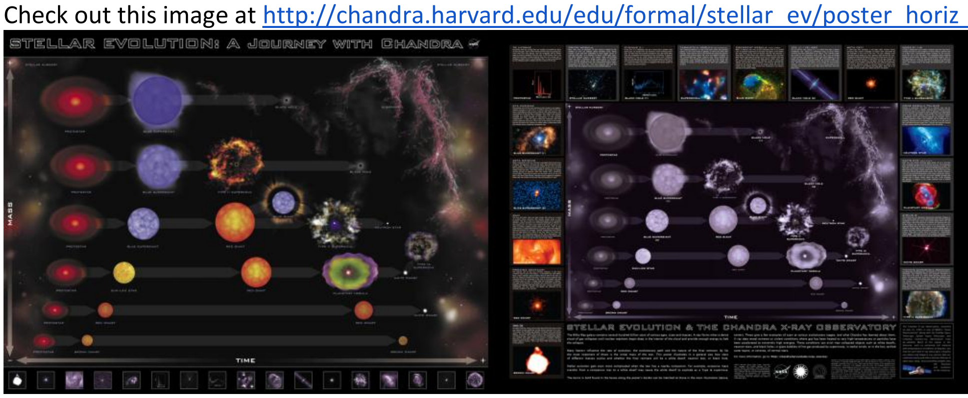
(*Sources*: http://en.wikipedia.org/wiki/Stellar_classification; http://en.wikipedia.org/wiki/Star, License: GNU-FDL)

For most stars, surface temperature is also related to size. Bigger stars produce more energy, so their surfaces are hotter. These stars tend toward bluish white. Smaller stars produce less energy. Their surfaces are less hot and so they tend to be yellowish.

1.6 Lifetime of Stars

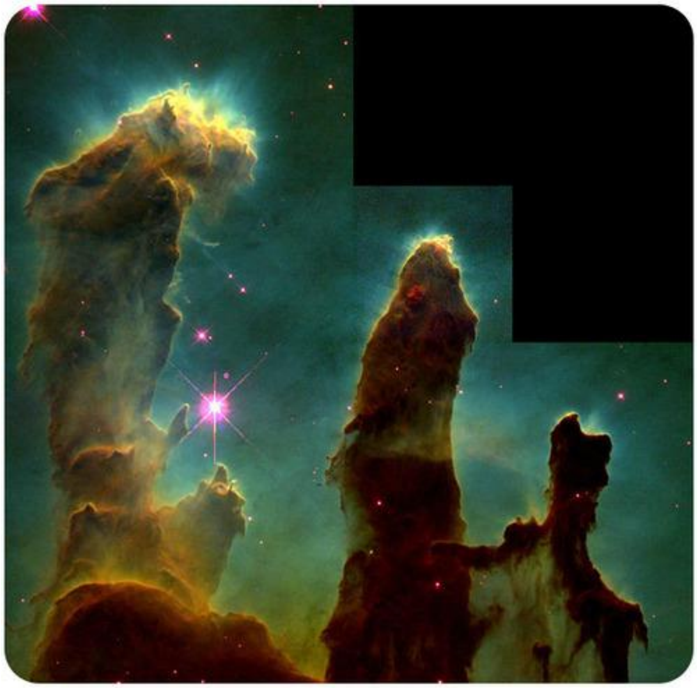
Stars have a life cycle that is expressed similarly to the life cycle of a living creature: they are born, grow, change over time, and eventually die. Most stars change in size, color, and class at least once in their lifetime. What astronomers know about the life cycles of stars is because of data gathered from visual, radio, and X-ray telescopes. In general, massive stars are large and live short lives, while low mass stars live a very long time. In fact, we have never seen white dwarfs, the longest living stars, die.

Check out this image at http://chandra.harvard.edu/edu/formal/stellar_ev/poster_horiz_med2.jpg



Star Formation

Stars are born in clouds of gas and dust called nebulas, like the one shown in **Figure** below and as described in the following section.
For more on star formation, check out http://www.spacetelescope.org/science/formation_of_stars.html and http://science1.nasa.gov/astrophysics/focus-areas/how-do-stars-form-and-evolve/.



The Pillars of Creation within the Eagle Nebula are where gas and dust come together as a stellar nursery.

The Main Sequence

For most of a star's life, nuclear fusion in the core produces helium from hydrogen. A star in this "adult" stage is a **main sequence** star. This term comes from the Hertzsprung-Russell diagram (H-R diagram) shown above. For stars that plot in the main sequence area of the H-R diagram, temperature is directly related to brightness. A star plots on the main sequence as long as it is able to balance the inward force of gravity with the outward force of nuclear fusion in its core. The more massive a star, the more it must fuse hydrogen fuel to prevent gravitational collapse. Because they "burn" more fuel, more massive stars have higher temperatures. Massive stars also run out of hydrogen sooner than smaller stars do.

Our Sun
Our Sun has been a main sequence star for about 5 billion years and will continue for about 5 billion more years (**Figure** below). Very large stars may graph on the main sequence for only 10 million years. Very small stars may last tens to hundreds of billions of years. Our Sun releases many different wavelengths of light, but the most frequent wavelength is yellow, which is why our sun is yellow. Our sun will become a red giant, then push off its

outer shell, and become a small white dwarf in about 5 billion years.

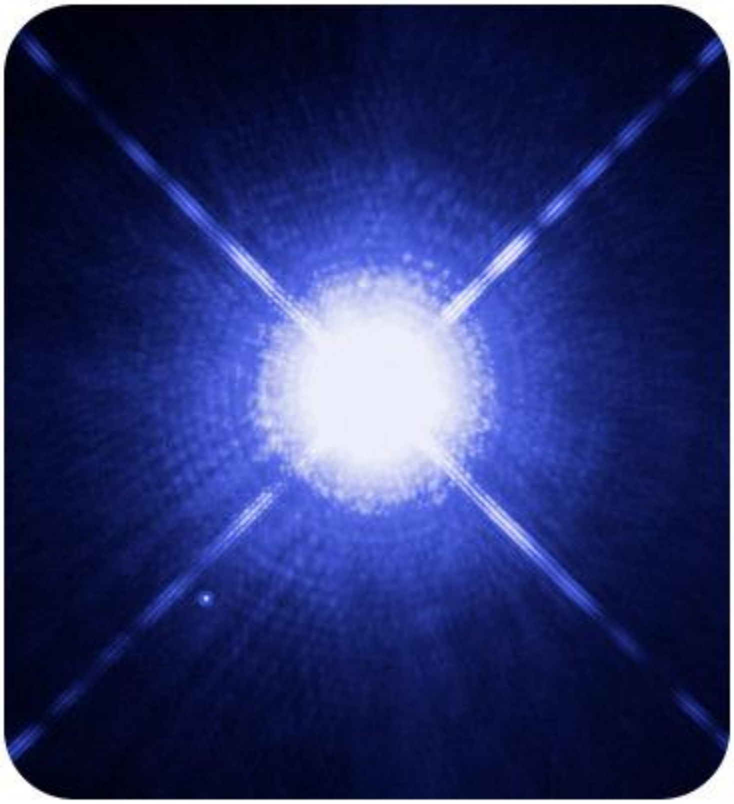
Our Sun is a medium-sized star in about the middle of its life.

The fate of the Sun and inner planets is explored in these videos:
http://videos.howstuffworks.com/science-channel/6566-destiny-the-suns-fate-video.htm (2:37)
http://www.youtube.com/watch?v=bhRiiay6Hs4 (3:32).

Red Giants and White Dwarfs

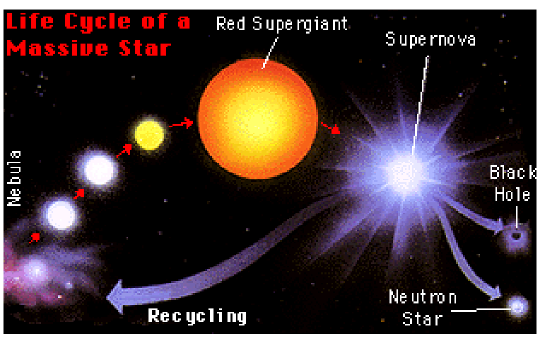
As a star begins to use up its hydrogen, it fuses helium atoms together into heavier atoms such as carbon. A blue giant star has exhausted its hydrogen fuel and is a transitional phase. When the light elements are mostly used up, the star can no longer resist gravity and it starts to collapse inward. The outer layers of the star grow outward and cool. The larger, cooler star is red in color and so is called a **red giant**.

Eventually, a red giant uses up all of the helium in its core. What happens next depends on how massive the star is. A typical star, such as the Sun, stops fusion completely. Gravitational collapse shrinks the star's core to a white, glowing object about the size of Earth, called a **white dwarf** (**Figure** below). A white dwarf will ultimately fade out.



Sirius, the brightest star in the sky, is actually a binary star system. Sirius A is on the main sequence. Sirius B, the tiny dot on the lower left, is a white dwarf.

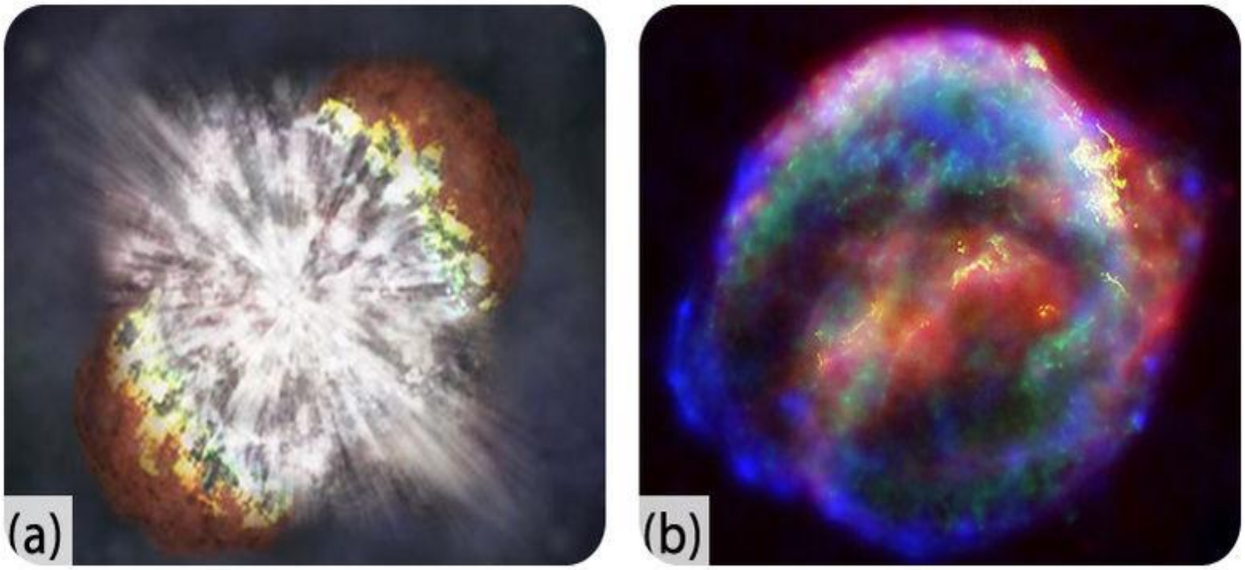
Supergiants and Supernovas



A star that runs out of helium will end its life much more dramatically than will the white dwarfs. When very massive stars use up all their helium, they no longer have the same direct relationship between brightness and temperature, so they no longer plot on the main sequence. Instead they get much larger and their surface is cooler, making them red supergiants (**Figure** below).

The red star Betelgeuse in Orion is a red supergiant.

Unlike a red giant, when all the helium in a red supergiant is gone, fusion continues. Lighter atoms fuse into heavier atoms up to iron atoms. Creating elements heavier than iron through fusion uses more energy than it produces so stars do not ordinarily form any heavier elements. When there are no more elements for the star to fuse, the core succumbs to gravity and collapses, creating a violent explosion called a **supernova** (**Figure** below). A supernova explosion contains so much energy that atoms fuse together to produce heavier elements such as gold, silver, and uranium. A supernova can shine as brightly as an entire galaxy for a short time. All elements with an atomic number greater than that of lithium were formed by nuclear fusion in stars.



(a) NASA's Chandra X-ray observatory captured the brightest stellar explosion so far, 100 times more energetic than a typical supernova. (b) This false-color image of the supernova remnant SN 1604 was observed as a supernova in the Milky Way galaxy. At its peak it was brighter than all other stars and planets, except Venus, in the night sky.

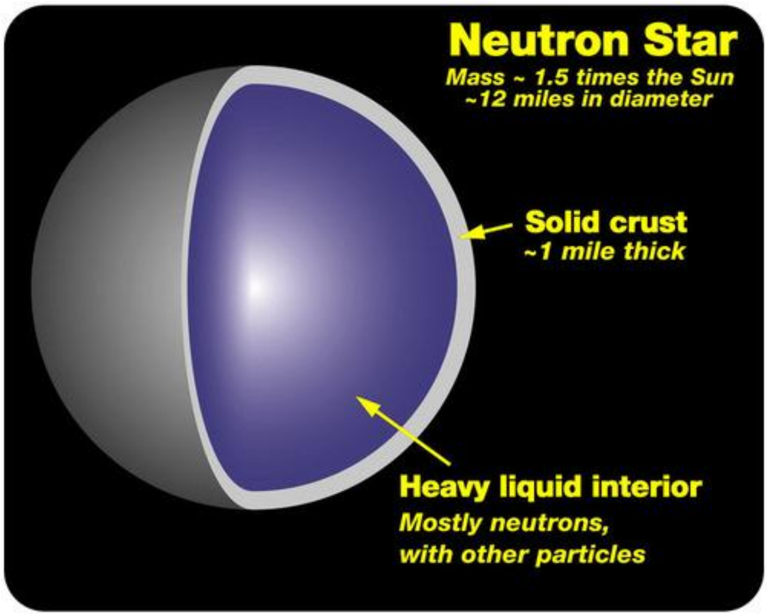
This animation shows a supernova: 
http://imagine.gsfc.nasa.gov/Images/basic/xray/supernova_anim.gif

An animation of the Crab Supernova is seen here: http://www.youtube.com/watch?v=WTKA2biEVgg (3:20)

This video looks at the origin of the universe, star formation, and the formation of the chemical elements in supernovas **(2c)**: http://www.youtube.com/watch?v=8AKXpBeddu0&feature=related(8:30)

Neutron Stars and Black Holes

After a supernova explosion, the leftover material in the core is extremely dense. If the core is less than about four times the mass of the Sun, the star becomes a **neutron star** (**Figure** below). A neutron star is made almost entirely of neutrons, relatively large particles that have no electrical charge. It is incredibly dense.

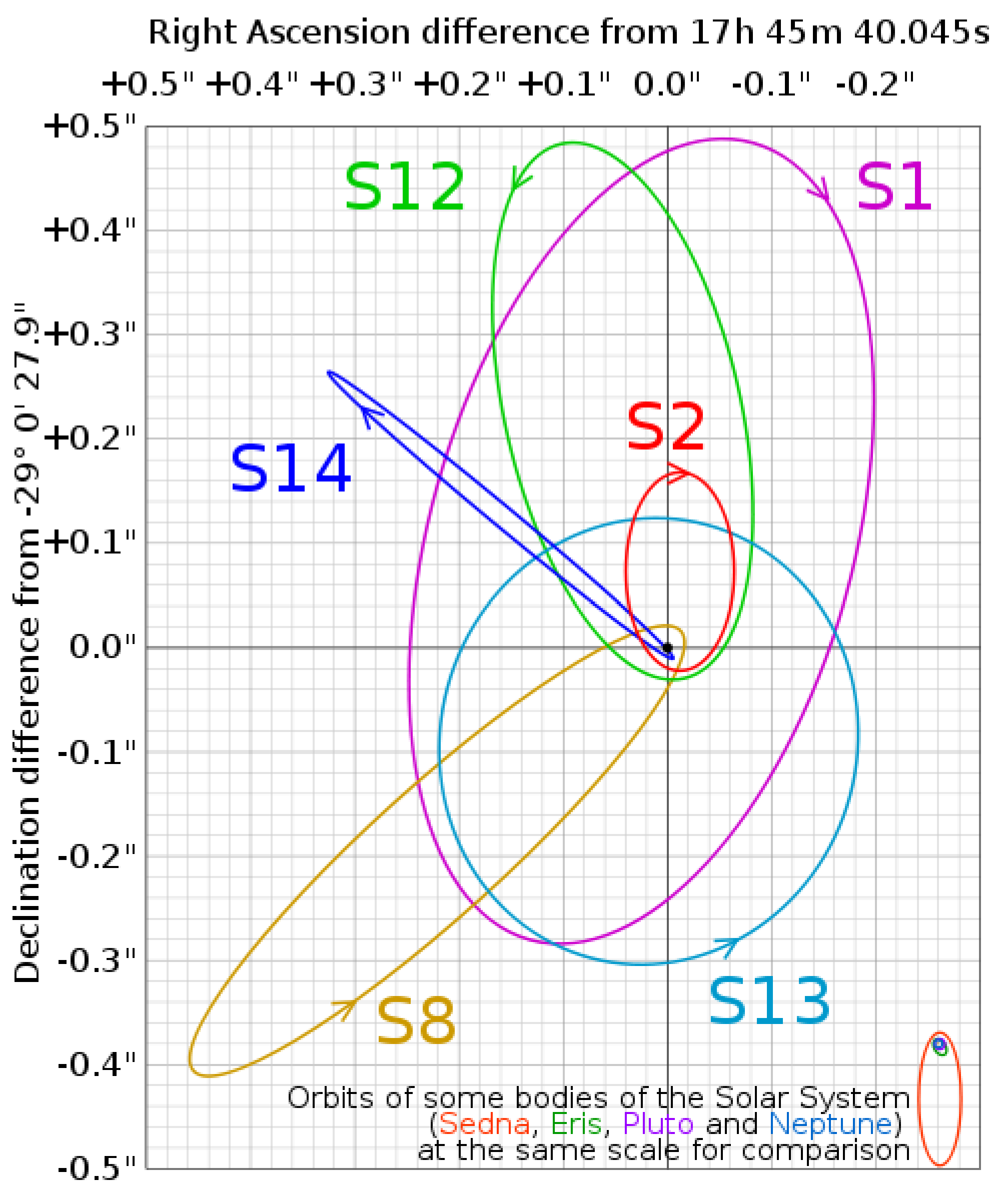


After a supernova, the remaining core may end up as a neutron star. A neutron star is more massive than the Sun, but only a few kilometers in diameter.

If the core remaining after a supernova is more than about five times the mass of the Sun, the core collapses into a **black hole**. Black holes are so dense that not even light can escape their gravity. With no light, a black hole cannot be observed directly. But a black hole can be identified by the effect that it has on objects around it, by the way it distorts light passing by it, and by radiation that leaks out around its edges.

Our Super Massive Black Hole

If you look into the night sky in the summer in Minnesota, after dark in the south you can see the constellation Saggitarius above the horizon. This asterism looks to many people like a teapot, and if you look in the area above the teapot's spout you are looking to the center of the Milky Way. There are many clusters of stars there, and at the very center we have evidence that there is a supermassive black hole.



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Because of the paths of these stars, we infer that there is something very massive at the center. (image from http://en.wikipedia.org/wiki/File:Galactic_centre_orbits.svg Creative Commons Attribution-Share Alike 3.0 Unported)

Gravitational Lensing

We cannot see a black hole, since no light escapes its surface. Additional evidence of the existence of black holes is how their gravity bends light, an effect called gravitational lensing. Gravitational Lensing videos:
http://www.spacetelescope.org/videos/hst15_chapter07/
http://www.spacetelescope.org/videos/heic0814f/

Hawking Radiation
In empty space particles and antiparticles can pop into existence out of the quantum foam at any time, as long as they don't exist for very long. But what happens if one of the pair is gravitationally attracted beyond a black hole's event horizon, and they cannot pair back up and annihilate each other? This video clip explains Hawking Radiation: http://www.youtube.com/watch?v=S6srN4idq1E

Peer into a simulated stellar-mass black hole:
http://www.youtube.com/watch?v=v02wYCo76KU (2:43)
A Star's Life Cycle video from Discovery Channel describes how stars are born, age and die **(2f)**:
http://www.youtube.com/watch?v=H8Jz6FU5D1A(3:11).

A video of neutron stars is available at: http://www.youtube.com/watch?v=VMnLVkV_ovc(4:24).

Lesson Summary

- Constellations and asterisms are apparent patterns of stars in the sky.
- Stars in the same constellation are often not close to each other in space.
- Parallax is an apparent shift in an object's position when the position of the observer changes. Astronomers use parallax to measure the distance to relatively nearby stars.
- A star generates energy by nuclear fusion reactions in its core.
- The color of a star is determined by its surface temperature.
- Stars are classified by color and temperature: O (blue), B (bluish white), A (white), F (yellowish white), G (yellow), K (orange), and M (red), from hottest to coolest.
- Stars form from nebulas. Gravity causes stars to collapse until nuclear fusion begins.
- Stars spend most of their lives on the main sequence, fusing hydrogen into helium.
- Typical, Sun-like stars expand into red giants, then fade out as white dwarfs.
- Very large stars expand into red supergiants, explode in supernovas, and end up as neutron stars or black holes.

Review Questions

1. What distinguishes a nebula and a star?
2. What kind of reactions provide a star with energy?
3. Stars are extremely massive. Why don't they collapse under the weight of their own gravity?
4. Of what importance are particle accelerators to scientists?
5. Which has a higher surface temperature: a blue star or a red star?
6. List the seven main classes of stars, from hottest to coolest.
7. What is the main characteristic of a main sequence star?
8. What kind of star will the Sun be after it leaves the main sequence?
9. Suppose a large star explodes in a supernova, leaving a core that is 10 times the mass of the Sun. What would happen to the core of the star?
10. Since black holes are black, how do astronomers know that they exist?
11. What is a light year?
12. Why don't astronomers use parallax to measure the distance to stars that are very far away?
13. What evidence do astronomers have to support the model of the life cycle of stars?

Further Reading / Supplemental Links

- Information on element formation in stars and supernova: http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/background-lifecycles.html and http://aether.lbl.gov/www/tour/elements/stellar/stellar_a.html
- Astronomy simulations: http://ww2.valdosta.edu/~cbarnbau/astro_demos/
- Myths and history of constellations: http://www.ianridpath.com/startales/contents.htm
- NASA World Book, Stars: http://www.nasa.gov/worldbook/star_worldbook.html
- NASA, parts of a star: http://imagine.gsfc.nasa.gov/docs/science/know_l1/stars.html
- CHANDRA X-ray Observatory website (educators can request stellar evolution teaching materials) http://chandra.harvard.edu/edu/formal/stellar_ev/
- ESA movies, “Eyes on the Skies” and Hubble: 15 years of discovery (educators can order free materials http://www.spacetelescope.org/shop/freeorder/)

Points to Consider

- Although stars may appear to be close together in constellations, they are usually not close together out in space. Can you think of any groups of astronomical objects that are relatively close together in space?
- Most nebulas contain more mass than a single star. If a large nebula collapsed into several different stars, what would the result be like?

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Do scientists just make this stuff up?
No! Although our Solar System formed nearly 5 billion years ago, we can see stars forming elsewhere in the galaxy, such as in the Large Magellanic cloud 160,000 light years away. Although we can't know for sure, astronomers think that our early solar system looked very much like this.

Section 2 <u>Formation of the Solar System</u>

Supporting Learning Target:

I can describe how the solar system formed.

Vocabulary

- nebula
- protoplanetary disk
- planetesimals

2.1 The Nebular Hypothesis

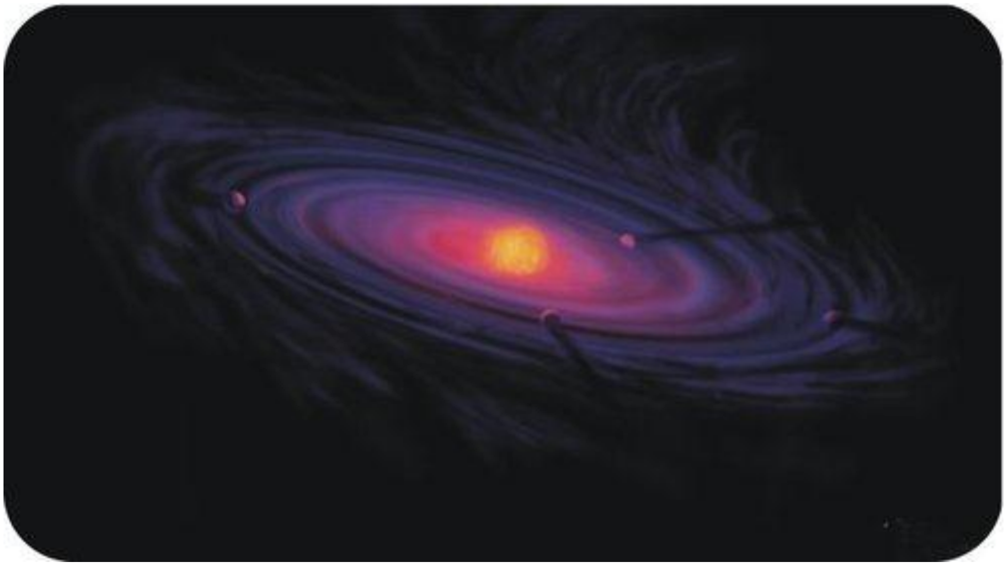
The most widely accepted scientific explanation of how the solar system formed is called the **nebular hypothesis**. According to this hypothesis, the Sun and the planets of our solar system formed about 4.6 billion years ago from the collapse of a giant cloud of gas and dust, called a **nebula**.

The nebula was drawn together by gravity, which caused the particles to accelerate. As small particles of dust and gas smashed together to create larger ones, they transformed their gravitational energy to kinetic energy and moved faster. As the nebula pulled itself together at the center, the mass there increased and so the gravity increased. As the gravity at the center increased, the cloud started to spin because of its angular momentum. As it collapsed further, the spinning got faster, much as an ice skater or basketball player spins faster when she pulls her arms to her sides during a spin.

Much of the cloud's mass migrated to its center but the rest of the material flattened out in an enormous protoplanetary disk. The disk contained hydrogen and helium, along with heavier elements and even simple organic molecules.

Formation of the Sun and Planets

As gravity pulled matter into the center of the disk, the density and pressure at the center became intense. When the pressure in the center of the disk was high enough, nuclear fusion began. A star was born—the Sun. The outward push of fusion and the inward pull of gravity in the "burning" star stopped the disk from collapsing further.



An artist's painting of a protoplanetary disk.

Meanwhile, the outer parts of the disk were cooling off. The small pieces of dust and gas started clumping together. These clumps collided and combined with other clumps. Larger clumps, called planetesimals, attracted smaller clumps with their gravity. The gravitational field, centered on the sun at the center of the disk, pulled more on heavier particles, such as rock and metal, than on lighter particles. The majority of the dense materials were pulled to the center while the majority of low density materials remained further out in the disk. This is why the inner planets are dense, made mostly of solid materials, while the outer planets are less dense, with much more gas. Eventually, the planetesimals formed protoplanets, which grew to become the planets and moons that we find in our solar system today.

Because of the gravitational sorting of material, the inner planets — Mercury, Venus, Earth, and Mars — formed from dense rock and metal. The outer planets — Jupiter, Saturn, Uranus and Neptune — condensed farther from the Sun from lighter materials such as hydrogen, helium, water, ammonia, and methane. Out by Jupiter and beyond, where it's very cold, these materials form solid particles.

The nebular hypothesis was designed to explain some of the basic features of the solar system:

- The orbits of the planets lie in nearly the same plane with the Sun at the center
- The planets revolve in the same direction
- The planets mostly rotate in the same direction
- The axes of rotation of the planets are mostly nearly perpendicular to the orbital plane
- The oldest moon rocks are 4.5 billion years

This video, from the ESA, discusses the Sun, planets, and other bodies in the Solar System and how they formed **(1a, 1d)**. The first part of the video explores the evolution of our view of the solar system starting with the early Greeks who reasoned that since some points of light - which they called planets - moved faster than the stars, they must be closer: http://www.youtube.com/watch?v=-NxfBOhQ1CY&feature=player_profilepage (8:34).

Summary

- A giant cloud of dust and gas, called a nebula, collapsed to form the solar system; this is the nebular hypothesis.
- The nebular hypothesis explains many of the features of the solar system like the orbital plane, the revolution and rotation of the planets, the relationship of the axes of rotation and the orbital plane and the age of moon rocks.
- Planets nearer the Sun are similar because they formed of denser metal and rocks, but planets further out are lighter and gaseous.

Practice

Use this resource to answer the questions that follow.
http://www.youtube.com/watch?v=B1AXbpYndGc

1. What is a protostar?
2. When does nuclear fusion begin?
3. When was our star born?
4. How long with the star burn?
5. How do scientists think our sun was born?
6. What was the Big Bang?

Review

1. What is the nebular hypothesis?
2. How do features we see elsewhere in our galaxy help us to understand the origin of our solar system?
3. How does the nebular hypothesis account for the observable features of the solar system?
4. What evidence supports the Nebular Hypothesis?

Further Reading / Supplemental Links

- Nova: solar system formation video: http://www.pbs.org/wgbh/nova/space/origins-solar-system.html (13:12)
- Tour the solar system: http://www.pbs.org/wgbh/nova/space/tour-solar-system.html
- A claim-evidence-reasoning driven view of solar system formation can be found here: http://lasp.colorado.edu/~bagenal/1010/SESSIONS/11.Formation.html
- Astronomy simulations: http://ww2.valdosta.edu/~cbarnbau/astro_demos/

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Section 3 Our Place in Space – The Milky Way Galaxy

Supporting Learning Target:

I can describe the relationships between the various structures of the universe.

Vocabulary

- galaxy
- Milky Way Galaxy
- spiral arm
- barred spiral galaxy
- star cluster
- star system

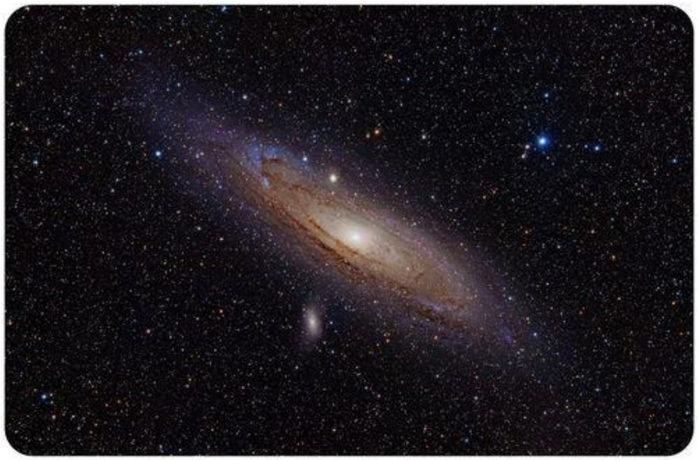
3.1 Introduction

Where do you live? Sure you live in a house or apartment, on a street, in a town or city, in a state, and in a country. You may not think to mention that you live on planet Earth in the solar system (as if there is no other), which is in the Milky Way Galaxy. Our galaxy is just one of many billions of galaxies in the universe. These galaxies are incomprehensible distances from each other and from Earth.

Usually the stars that we see near each other in our night sky, the constellations, are not physically close together. A few, though, may be found in the same portion of space. Stars that are grouped closely together are called **star systems**. Larger groups of hundreds or thousands of stars are called **star clusters**.

Galaxies are the biggest groups of stars and can contain anywhere from a few million stars to many billions of stars. Galaxies exist in spiral, elliptical, or irregular shapes. Spiral galaxies contain lots of gas, dust, and young stars. Most elliptical galaxies contain little gas and dust and mostly old stars. Based on evidence, scientists think irregular galaxies were once spiral or elliptical and became deformed through gravitational attraction with a larger galaxy or a collision with another galaxy.

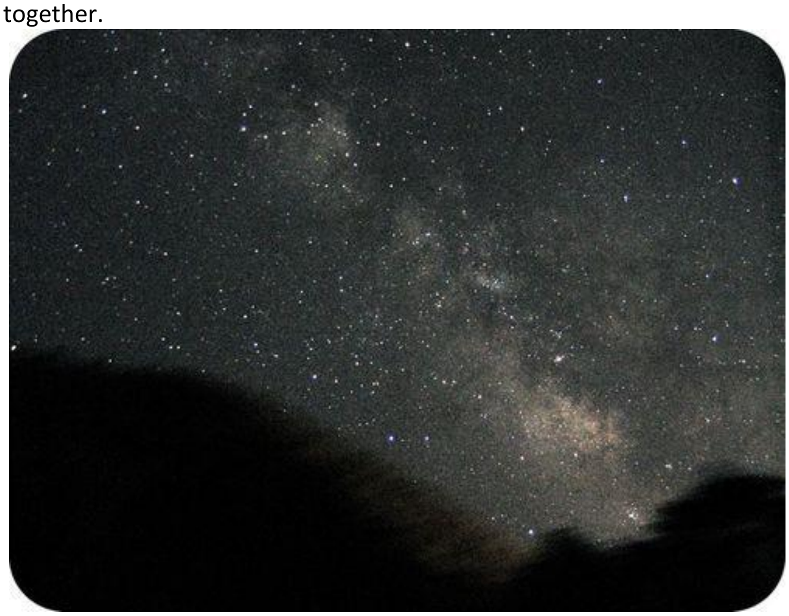
Every star that is visible in the night sky is part of the Milky Way Galaxy. To the naked eye the closest major galaxy — the Andromeda Galaxy, shown in **Figure** below — looks like only a dim, fuzzy spot. But that fuzzy spot contains one trillion stars -- 1,000,000,000,000 stars!



The Andromeda Galaxy is a large spiral galaxy similar to the Milky Way.

3.2 The Milky Way Galaxy

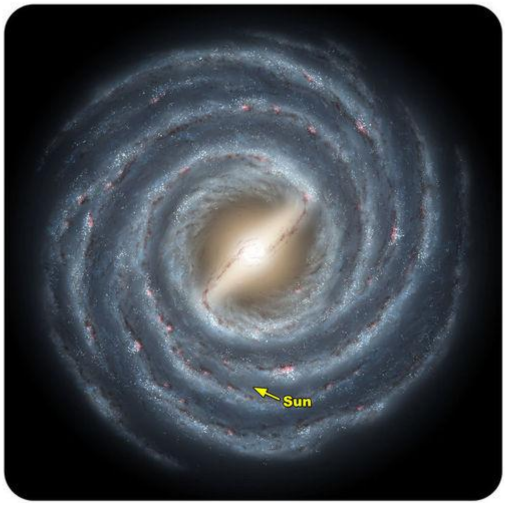
On a dark, clear night, you will see a milky band of light stretching across the sky, as in **Figure** below. This band is the disk of a galaxy, the **Milky Way Galaxy**, which is our galaxy. The Milky Way is made of millions of stars along with a lot of gas and dust. Like other galaxies, the stars, dust and gas in the Milky Way are gravitationally bound together.



The Milky Way Galaxy looks different than other galaxies because we are looking along the main disk from within the galaxy.

Shape and Size

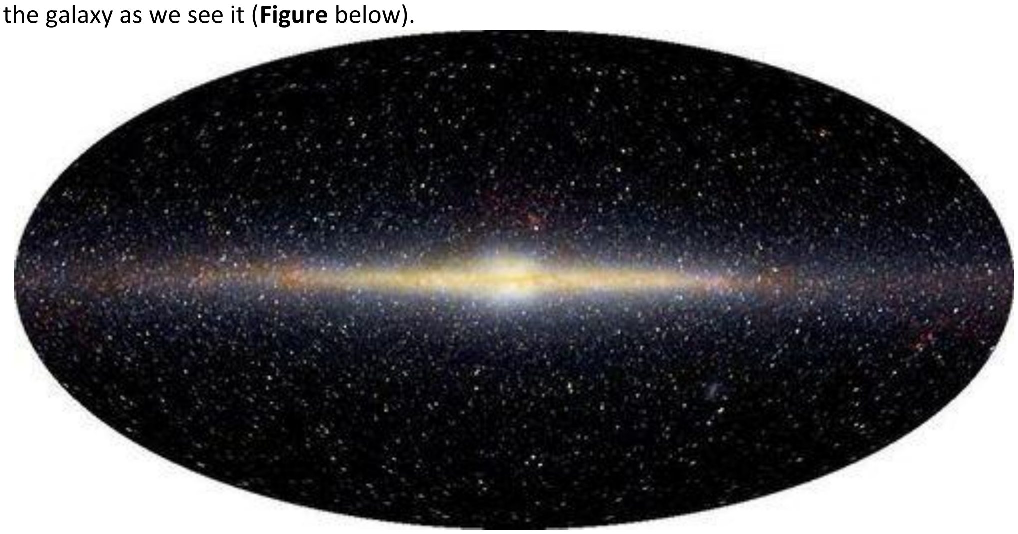
Although it is difficult to know what the shape of the Milky Way Galaxy is because we are inside of it, astronomers have identified it as a typical barred spiral galaxy containing about 100 billion to 400 billion stars (**Figure** below).



An artist's rendition of what astronomers think the Milky Way Galaxy would look like seen from far above our North Pole. The Sun is located approximately where the arrow points.

Like other spiral galaxies, our galaxy has a disk, a central bulge, and spiral arms. The disk is about 100,000 light-years across and 3,000 light-years thick. Most of the Galaxy's gas, dust, young stars, and open clusters are in the disk. What evidence do astronomers find that lets them know that the Milky Way is a spiral galaxy?

1. The shape of the galaxy as we see it (**Figure** below).

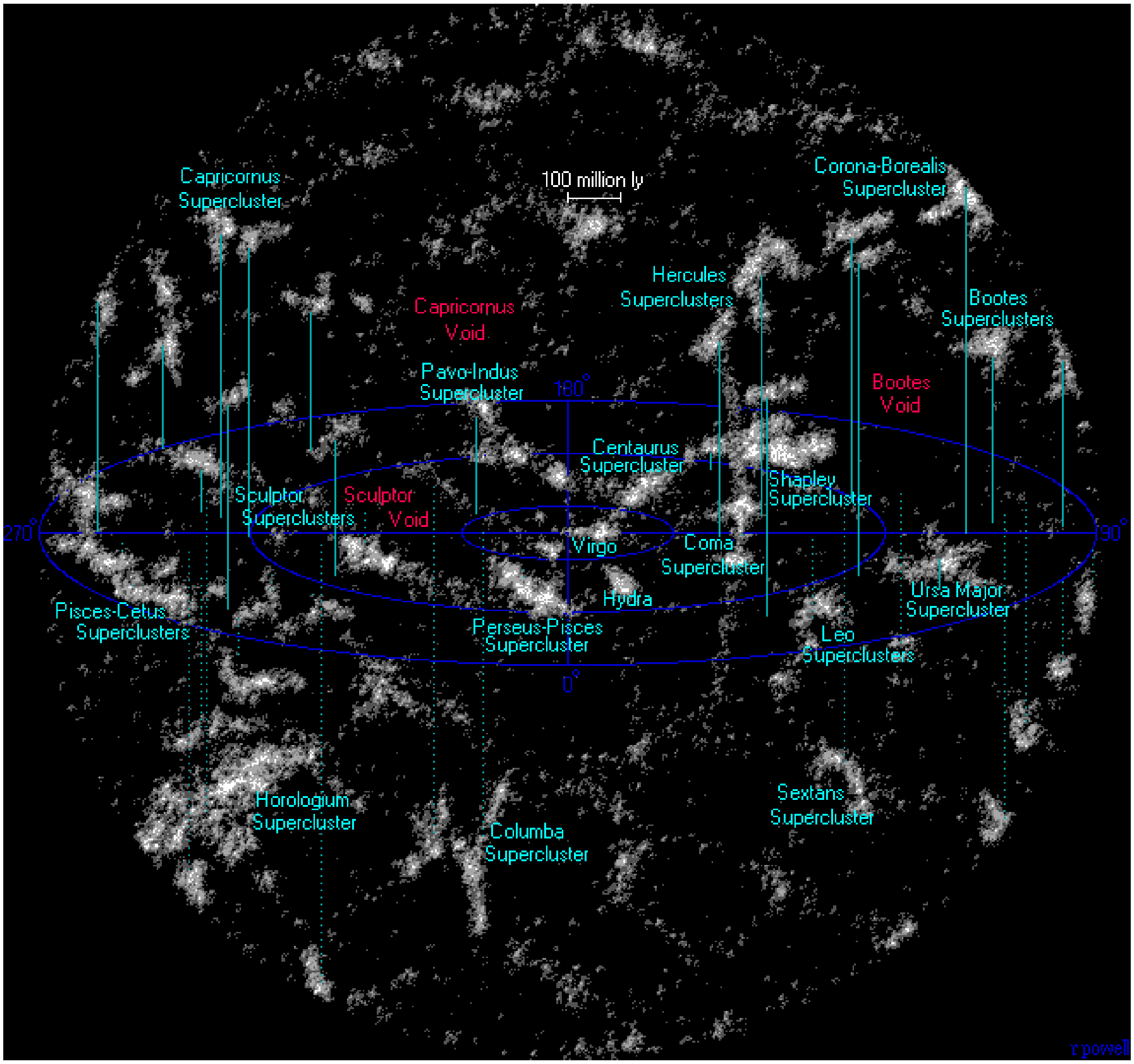


An infrared image of the Milky Way shows the long thin line of stars and the central bulge typical of spiral galaxies.

2. The velocities of stars and gas in the galaxy show a rotational motion.
3. The gases, color, and dust are typical of spiral galaxies.

The central bulge is about 12,000 to 16,000 light-years wide and 6,000 to 10,000 light-years thick. The central bulge contains mostly older stars and globular clusters. Some recent evidence suggests the bulge might not be spherical, but is instead shaped like a bar. The bar might be as long as 27,000 light-years long. The disk and bulge are surrounded by a faint, spherical halo, which also contains old stars and globular clusters. Astronomers have discovered that there is a gigantic black hole at the center of the galaxy.

The Milky Way Galaxy is a big place. If our solar system were the size of your fist, the Galaxy's disk would still be wider than the entire United States! A video close-up of the Milky Way Galaxy is seen here: http://science.discovery.com/video-topics/space-videos/space-school-milky-way.htm (5:39)



*

The universe within 1 billion light years of Earth, showing local superclusters. Approximately 63 million galaxies are shown. In this image we are at the center.
By Richard Powell [Creative Commons](#) [Attribution-Share Alike 2.5 Generic](#) (image from https://en.wikipedia.org/wiki/File:Superclusters_atlasoftheuniverse.gif)

Our galaxy, the Milky Way, will someday change from being a barred spiral galaxy to being an irregular galaxy after our collision with the Andromeda Galaxy. Learn more about it in this “Clash of the Titans” video: http://www.spacetelescope.org/videos/hubblecast55a/

This galaxy, called NGC 1427A, has neither a spiral nor an elliptical shape.

Where We Are

Our solar system, including the Sun, Earth, and all the other planets, is within one of the spiral arms in the disk of the Milky Way Galaxy. Most of the stars we see in the sky are relatively nearby stars that are also in this spiral arm. We are about 26,000 light-years from the center of the galaxy, a little more than halfway out from the center of the galaxy to the edge.

Just as Earth orbits the Sun, the Sun and solar system orbit the center of the Galaxy. One orbit of the solar system takes about 225 to 250 million years. The solar system has orbited 20 to 25 times since it formed 4.6 billion years ago. Astronomers have recently discovered that at the center of the Milky Way, and most other galaxies, is a supermassive black hole, although a black hole cannot be seen.

This video describes the solar system in which we live. It is located in an outer edge of the Milky Way galaxy, which spans 100,000 light years **(2a)**: http://www.youtube.com/watch?v=0Rt7FevNiRc (5:10).

The Universe contains many billions of stars and there are many billions of galaxies. Our home, the Milky Way galaxy, is only one **(2a, 2b)**: http://www.youtube.com/watch?v=eRJvB3hM7K0&feature=related (5:59).

Here is a short NASA video on galaxy formation:
http://www.nasa.gov/multimedia/videogallery/index.html?media_id=154188551

Lesson Summary

- Many stars are in systems of two or more stars.
- Star clusters contain hundreds or thousands of stars grouped together.
- Galaxies are collections of millions to many billions of stars.
- The Milky Way Galaxy is a typical spiral galaxy. Our solar system is in a spiral arm of the Milky Way Galaxy, a little more than halfway from the center to the edge of the disk.

Review Questions

1. List three main features of a spiral galaxy.
2. What galaxy do we live in, and what kind of galaxy is it?
3. What is the evidence that the galaxy we live in is this type of galaxy?
4. Describe the location of our solar system in our galaxy.

Further Reading / Supplemental Links

- Variety of astronomy news: http://www.space.com
- More about galaxies and their shapes: http://stardate.org/resources/btss/galaxies/
- Learn more about the future of the Milky Way in the "Clash of the Titans" video: http://www.spacetelescope.org/videos/hubblecast55a/
- For more information about galaxy evolution and the James Webb Space Telescope watch: http://www.youtube.com/watch?v=C6vxOchSzsM
-

Points to Consider

- Objects in the universe tend to be grouped together. What forces or factors do you think cause objects to form and stay in groups?
- Some people used to call galaxies "island universes." Are they really universes?
- Can you think of anything, either an object or a group of objects, that is bigger than a galaxy?

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Section 4 The Universe and Cosmology

Supporting Learning Target:

I can construct an explanation of the Big Bang theory based on astronomical evidence.

I can explain how the rules of the Universe can be discovered, and the implication that those rules are the same everywhere.

I can describe the relationships between the various structures of the universe.

- Explain the evidence for an expanding universe.
- Tell the story of the universe from the Big Bang into the future.
- Cite the evidence for dark matter and dark energy.

Vocabulary

- Big Bang Theory
- cosmology
- dark energy
- dark matter
- Doppler effect
- redshift
- universe

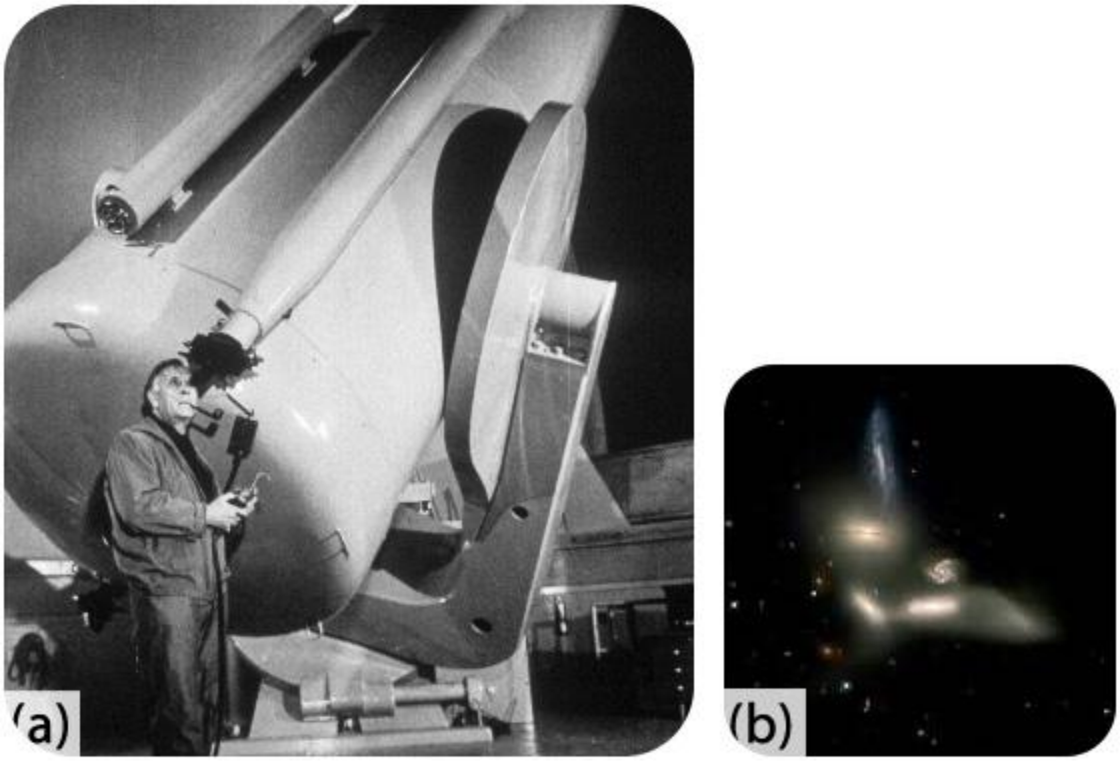
4.1 Introduction

For a long time humans thought the earth and the sky was the whole universe. Until the 1930s we thought that the Milky Way was the entire universe. Now we know our solar system is one of many in the galaxy, and our galaxy is one of many billions in our universe. The study of the universe is called **cosmology**. Cosmologists study the structure and changes in the present universe. The **universe** contains all of the star systems, galaxies, gas and dust, plus all the matter and energy that exists now, that existed in the past, and that will exist in the future. The universe includes all of space and time.

4.2 Evolution of Human Understanding of the Universe

What did the ancient Greeks recognize as the universe? In their model, the universe contained Earth at the center, the Sun, the Moon, five planets, and a sphere to which all the stars were attached. This idea held for many centuries until Galileo's telescope helped allow people to recognize that Earth is not the center of the universe. They also found out many more stars exist than were visible to the naked eye. All of those stars were in the Milky Way Galaxy.

In the early 20th century, an astronomer named Edwin Hubble (**Figure** below) discovered what scientists called the Andromeda Nebula was actually over 2 million light years away — many times farther than the farthest distances that had ever been measured. Hubble realized many of the objects astronomers called nebulas were not actually clouds of gas, but were collections of millions or billions of stars — what we now call galaxies.



(a) Edwin Hubble used the 100-inch reflecting telescope at the Mount Wilson Observatory in California to show that some distant specks of light were galaxies. (b) Hubble's namesake space telescope spotted this six galaxy group. Edwin Hubble demonstrated the existence of galaxies.

Hubble showed the universe was much larger than our own galaxy. Today, we know the universe contains about a hundred billion galaxies—about the same number of galaxies as there are stars in the Milky Way Galaxy.

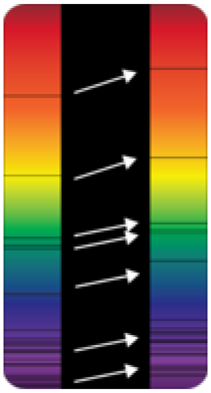
4.3 Expansion of the Universe

After discovering galaxies beyond the Milky Way, Edwin Hubble went on to measure the distance to hundreds of other galaxies. His data would eventually show how the universe is changing, and would even yield clues as to how the universe formed.

Redshift

If you look at a star through a prism, you will see a spectrum, or a range of colors through the rainbow. The spectrum will have specific dark bands where elements in the star absorb light of certain energies. By examining the arrangement of these dark absorption lines, astronomers can determine the composition of elements that make up a distant star. In fact, the element helium was first discovered in our Sun — not on Earth — by analyzing the absorption lines in the spectrum of the Sun.

While studying the spectrum of light from distant galaxies, astronomers noticed something strange. The dark lines in the spectrum were in the patterns they expected, but they were shifted toward the red end of the spectrum, as shown in **Figure** below. This shift of absorption bands toward the red end of the spectrum is known as **redshift**.



Redshift is a shift in absorption bands toward the red end of the spectrum. What could make the absorption bands of a star shift toward the red?

Redshift occurs when the light source is moving away from the observer or when the space between the observer and the source is stretched. What does it mean that stars and galaxies are redshifted? When astronomers see redshift in the light from a galaxy, they know that the galaxy is moving away from Earth.

If galaxies were moving randomly, would some be redshifted but others be blueshifted? Of course. Since almost every galaxy in the universe has a redshift, almost every galaxy is moving away from Earth.

Redshift can occur with other types of waves too. This phenomenon is called the **Doppler Effect**. An analogy to redshift is the noise a siren makes as it passes you. You may have noticed that an ambulance seems to lower the pitch of its siren after it passes you. The sound waves shift towards a lower pitch when the ambulance speeds away from you. Though redshift involves light instead of sound, a similar principle operates in both situations.

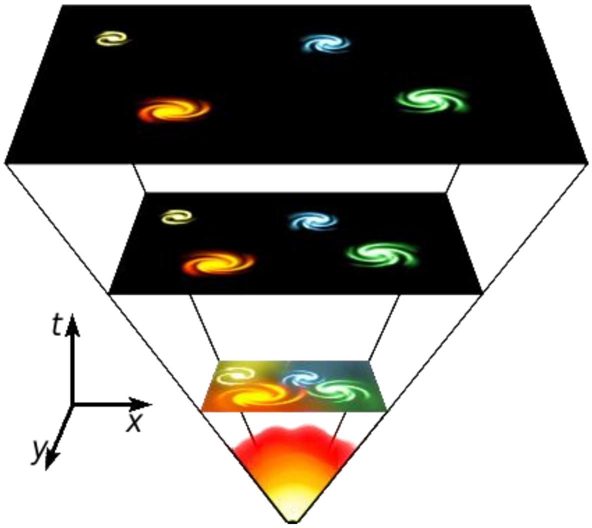
An animation of Doppler Effect http://projects.astro.illinois.edu/data/Doppler/index.html.

The Expanding Universe

Edwin Hubble combined his measurements of the distances to galaxies with other astronomers' measurements of redshift. From this data, he noticed a relationship, which is now called Hubble's Law: The farther away a galaxy is, the faster it is moving away from us. What could this mean about the universe? It means that the universe is expanding. This relationship is quantified in Hubble's Constant, H, and describes how much space is expanding by each second: 67.80 ± 0.77 (km/s)/Mpc.

Figure below shows a simplified diagram of the expansion of the universe. One way to picture this is to imagine a balloon covered with tiny dots to represent the galaxies. When you inflate the balloon, the dots slowly move away from each other because the rubber stretches in the space between them. If you were standing on one of the dots, you would see the other dots moving away from you. Also the dots farther away from you on the balloon would move away faster than dots nearby.

Expansion of the Universe Diagram



In this diagram of the expansion of the universe over time, the distance between galaxies gets bigger over time, although the size of each galaxy stays the same.

An inflating balloon is only a rough analogy to the expanding universe for several reasons. One important reason is the surface of a balloon has only two dimensions, while space has three dimensions. But space itself is stretching out between galaxies like the rubber stretches when a balloon is inflated. This stretching of space, which increases the distance between galaxies, is what causes the expansion of the universe.
An animation of an expanding universe is shown here:
http://www.astro.ubc.ca/~scharein/a311/Sim/bang/BigBang.html.
One other difference between the universe and a balloon involves the actual size of the galaxies. On a balloon, the dots will become larger in size as you inflate it. In the universe, the galaxies stay the same size, just the space between the galaxies increases.

4.4 Formation of the Universe

Before Hubble, most astronomers thought that the universe didn't change. But if the universe is expanding, what does that say about where it was in the past? If the universe is expanding, the next logical thought is that in the past it had to have been smaller.

The Big Bang Theory

The **Big Bang theory** is the most widely accepted cosmological explanation of how the universe formed. If we start at the present and go back into the past, the universe is contracting -- getting smaller and smaller. What is the end result of a contracting universe?
When we use the word theory in science, it means something different than when we use it in casual conversation. It means the best, most complete explanation in science, whereas in casual conversation it often means a poorly formed idea. The Big Bang theory is the best explanation to date about how the universe became what it is today. According to the Big Bang theory, the universe began about 13.81 billion years ago. Everything that is now in the universe was squeezed into a very small volume. Imagine all of the known universe in a single, hot, chaotic mass. An enormous explosion — a big bang — caused the universe to start expanding rapidly. All the matter and energy in the universe, and even space itself, came out of this explosion.

What came before the Big Bang? There is no way for scientists to know since there is no remaining evidence.

After the Big Bang

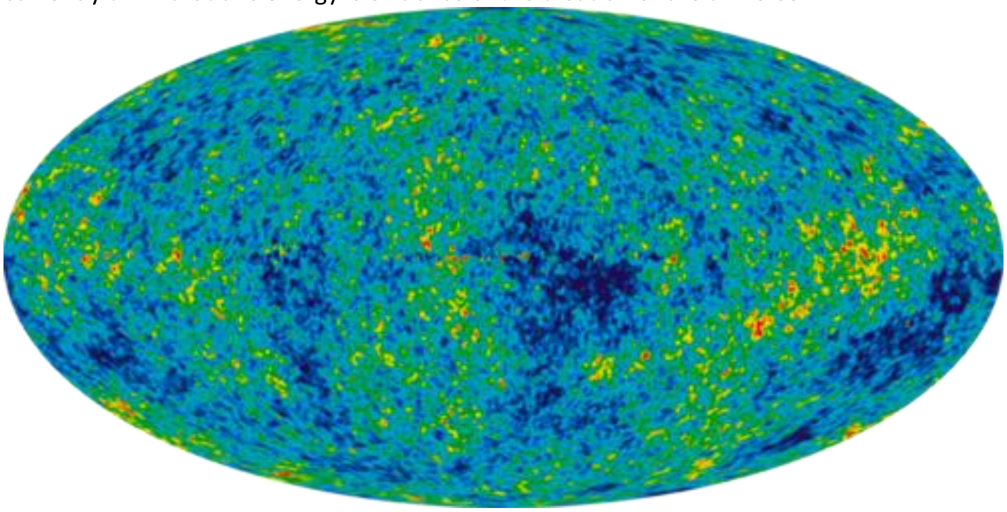
In the first few moments after the Big Bang, the universe was unimaginably hot and dense. As the universe expanded, it became less dense and began to cool. After only a few seconds, protons, neutrons, and electrons could form. After a few minutes, those subatomic particles came together to create hydrogen. Energy in the universe was great enough to initiate nuclear fusion and hydrogen nuclei were fused into helium nuclei. The first neutral atoms that included electrons did not form until about 380,000 years later.

The matter in the early universe was not smoothly distributed across space. Dense clumps of matter held close together by gravity were spread around. Eventually, these clumps formed countless trillions of stars, billions of galaxies, and other structures that now form most of the visible mass of the universe.

If you look at an image of galaxies at the far edge of what we can see, you are looking at great distances. But you are also looking across a different type of distance. What do those far away galaxies represent? Because it takes so long for light from so far away to reach us, you are also looking back in time (**Figure** below).

Images from very far away show what the universe was like not too long after the Big Bang.

After the origin of the Big Bang hypothesis, many astronomers still thought the universe was static. Nearly all came around when an important line of evidence for the Big Bang was discovered in 1964. In a static universe, the space between objects should have no heat at all; the temperature should measure 0 K (Kelvin is an absolute temperature scale). But two researchers at Bell Laboratories used a microwave receiver to learn that the background radiation in the universe is not 0 K, but 3 K (**Figure** below). What could this evidence mean? We currently think that this energy is evidence of the creation of the universe.



Background radiation in the universe was good evidence for the Big Bang Theory.

Hydrogen/Helium Distribution in the Early Universe

As we look at the universe and the matter we can see, we notice helium is abundant. As you know from learning about fusion in stars, hydrogen is fused into helium. If there was no big bang, and the universe was entirely hydrogen (atomic mass of 1), then there hasn't been enough time for the current ratio of hydrogen to helium. If in fact there was a big bang, then the temperatures which must have been present in the universe shortly after it formed were high enough to fuse hydrogen into helium, and result in the ratio we see, of about 3/4 hydrogen and 1/4 helium.

An explanation of the Big Bang: http://dvice.com/archives/2009/08/big-bang-animat.php.
How we know about the early universe: http://www.youtube.com/watch?v=uihNu9Icaeo&feature=channel (9:20).
History of the Universe, part 2: http://www.youtube.com/watch?v=bK6_p5a-Hbo&feature=channel (8:05). *The Evidence for the Big Bang in 10 Little Minutes* provides a great deal of scientific evidence for the Big Bang **(2g)**: http://www.youtube.com/watch?v=uyCkADmNdNo (10:10).

KQED: Nobel Laureate George Smoot and the Origin of the Universe

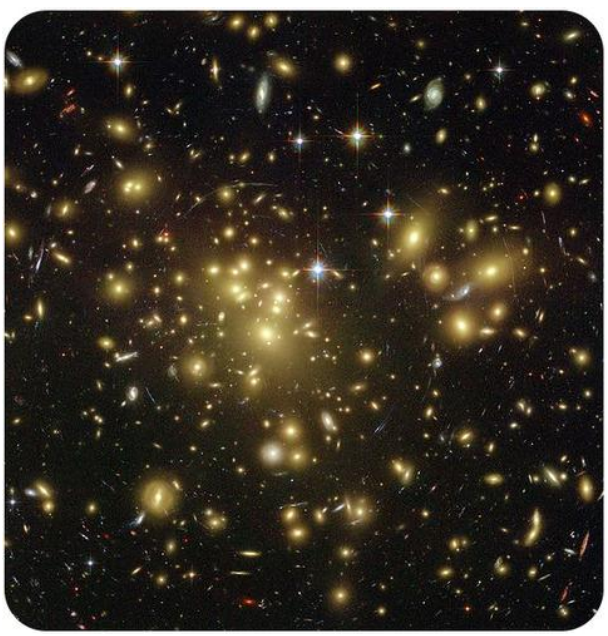
George Smoot, a scientist at Lawrence Berkeley National Lab, shared the 2006 Nobel Prize in Physics for his work on the origin of the universe. Using background radiation detected by the Cosmic Background Explorer Satellite (COBE), Smoot was able to make a picture of the universe when it was 12 hours old. Learn more at: http://science.kqed.org/quest/video/nobel-laureate-george-smoot-and-the-origin-of-the-universe/.

From Evidence to Explanation

The Big Bang theory is still the best scientific model we have for explaining the formation of the universe and many lines of evidence support it. However, recent discoveries continue to shake up our understanding of the universe. Astronomers and other scientists are now wrestling with some unanswered questions about what the universe is made of and why it is expanding. A lot of what cosmologists do is create mathematical models and computer simulations to account for these unknown phenomena.

4.5 Dark Matter

Vera Rubin, astronomer, was observing other galaxies, and saw something unusual in their rotational velocities. The outside edges of a galaxy rotate at the same speed as parts closer to the center. Based on the amount of mass she observed from all the stars, the galaxies were moving much too fast. What could explain their speed?
When we look at distant galaxies, the light from them is distorted. Because light can be "bent" by the gravity of matter, this gravitational lensing indicates that there is a large amount of unseen matter between us and the light of the distant galaxies. [Gravitational lensing occurs when light is bent from a very distant bright source around a super-massive object (**Figure** below).]
Scientists now think that there is matter that is making these galaxies rotate so fast, but that this matter is "dark" because it doesn't give off light, and we can't sense it in any way but its gravitational effects. The things we observe in space are objects that emit some type of electromagnetic radiation (light). However, scientists think that regular matter (baryonic matter) that emits light makes up only a small part of the matter in the universe, based on the rotational speeds of galaxies and the gravitational lensing of distant galaxies. The rest of the matter, about 80%, is dark matter.



The arc around the galaxies at the center of this image is caused by gravitational lensing. The addition of gravitational pull from dark matter is required to explain this phenomenon.

With so little to go on, astronomers don't really know much about the nature of dark matter. One possibility is that it could just be ordinary matter that does not emit radiation in objects such as black holes, neutron stars, and brown dwarfs -- objects larger than Jupiter but smaller than the smallest stars. But astronomers cannot find

enough of these types of objects, which they have named MACHOS (massive astrophysical compact halo object), to account for all the dark matter, so they are thought to be only a small part of the total.
Another possibility is that the dark matter is thought to be much different from the ordinary matter we see. Some appear to be particles that have gravity, but don't otherwise appear to interact with other particles. Scientists call these theoretical particles WIMPs, which stands for Weakly Interactive Massive Particles.
Most scientists who study dark matter think that the dark matter in the universe is a combination of MACHOS and some type of exotic matter such as WIMPs. Researching dark matter is an active area of scientific research, and astronomers' knowledge about dark matter is changing rapidly.
A video explaining dark matter is here: http://www.youtube.com/watch?v=gCgTJ6ID6ZA .

4.6 Future of our Universe

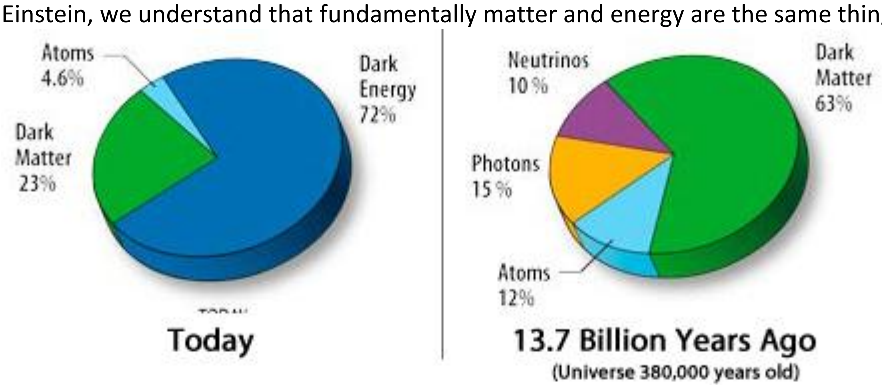
Astronomers who study the expansion of the universe are interested in knowing the rate of that expansion (Hubble's constant). They are also interested in the amount of matter in the universe, because all matter affects all other matter through gravity. Remember, The closer two objects are, the greater their gravitational interaction. The larger the two objects are, the greater their gravitational attraction. The Earth's gravity pulls of you, and your relatively tiny mass pulls on the Earth.
So what is the effect of the rate of expansion, versus the attractive pull of gravity?

- If yes, then the universe will expand forever, although the expansion could slow down or speed up.
- The outward expansion is perfectly balanced by the pull of gravity and the universe is constant.
- If no, then the universe would someday start to contract, and eventually get squeezed together in a big crunch, the opposite of the Big Bang.

Recently astronomers have made a discovery that answers this question: the rate at which the universe is expanding is actually increasing. In other words, the universe is expanding faster now than ever before, and in the future it will expand even faster! So now astronomers think that the universe will keep expanding forever.

Dark Energy

But this evidence also proposes a perplexing new question: What is causing the expansion of the universe to accelerate? Our current explanation, hypothesis, proposes the idea of **dark energy** (**Figure** below). It can be said that it is *as if* there was something there in empty space providing a repulsive force that makes the universe expand. This has been named **dark energy.** Recent data from the Planck mission by the European Space Agency indicates that dark energy makes up as much as 68.3% of the total energy content of the universe. All matter makes of the remaining amount of mass-energy, and regular matter (us, stars, dust) are 4.9%, and 28.6% dark matter. At the beginning, all the energy and mass of the universe were present. With the E=m*c*c equation from Einstein, we understand that fundamentally matter and energy are the same thing.



Today matter makes up a small percentage of the universe, but at the start of the universe it made up much more. Where did dark energy, if it even exists, come from?

Other scientists have different hypotheses about why the universe is continuing to expand. The causes of the universe's expansion is another unanswered question scientists are researching.

KQED: Dark Energy

Meet one of the three winners of the 2011 Nobel Prize in Physics, Lawrence Berkeley Lab astrophysicist Saul Perlmutter. He explains how dark energy, which makes up about 70 percent of the universe, is causing our universe to expand. Learn more at: http://science.kqed.org/quest/video/dark-energy/.

Lesson Summary

- The universe contains all the matter and energy that exists now, that existed in the past, and that will exist in the future. The universe also includes all of space and time.
- Redshift is a shift of element lines toward the red end of the spectrum. Redshift occurs when the source of light is moving away from the observer.
- Light from almost every galaxy is redshifted. The farther away a galaxy is, the more its light is redshifted, and the faster it is moving away from us.
- The redshift of galaxies means that the universe is expanding.
- The universe was squeezed into a very small volume and then exploded in the Big Bang theory about 13.81 billion years ago.
- Recent evidence shows that there is a lot of matter in the universe that we cannot detect directly. This matter is called dark matter.
- The rate of the expansion of the universe is increasing. The cause of this increase is unknown; one possible explanation involves a new form of energy called dark energy.

Review Questions

1. What is redshift, and what causes it to occur? What does redshift indicate?
2. What is Hubble's law?
3. What is the cosmological theory of the formation of the universe called?
4. How old is the universe, according to the Big Bang theory?
5. Describe at least two pieces of evidence that supports the Big Bang theory.
6. Describe two different possibilities for the nature of dark matter.
7. What makes scientists believe that dark matter exists?
8. What observation caused astronomers to propose the existence of dark energy?

Further Reading / Supplemental Links

- The science of dark matter: http://cdms.berkeley.edu/Education/DMpages/index.shtml
- More about cosmology: http://stardate.org/resources/btss/cosmology/
- Hyperphysics Astrophysics page: http://hyperphysics.phy-astr.gsu.edu/hbase/astro/astcon.html#c1
- Lab activities related to the expanding universe: http://www.planetseed.com/laboratory/experiment-hubble-constant and http://www.planetseed.com/laboratory/experiment-expanding-balloon

Points to Consider

- The expansion of the universe is sometimes modeled using a balloon with dots marked on it, as described earlier in the lesson. In what ways is this a good model, and it what ways does it not correctly represent the expanding universe? Can you think of a different way to model the expansion of the universe?
- The Big Bang theory is currently the most widely accepted scientific theory for how the universe formed. What is another explanation of how the universe could have formed? Is your explanation one that a scientist would accept?

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Section 5 The Standard Model

Learning Target 8.11:

I can explain how the rules of the Universe can be discovered, and the implication that those rules are the same everywhere.

Vocabulary

- particle accelerator
- standard model
- quark
- weak nuclear force
- strong nuclear force
- photon
- neutrino

5.1 Understanding the Nature of the Universe

Through testing, analysis, discussion, and revision, scientists continually work to discover and define the rules of the universe. These rules help scientists to explain events in the natural world, understand patterns, and make useful predictions. The rules here on Earth are the same as those across the universe. In order to understand more about the origin and nature of the universe and all of the forces, energy, and particles within, scientists must look at how they interact.

In **particle accelerators**, such as Fermilab, SLAC, and CERN, subatomic particles are propelled until they have attained almost the same amount of energy as found in the core of a star (Figure below). The larger and more expensive the accelerator, the higher the amount of energy it uses and the more we can understand about the origin of our universe. When these particles collide head-on, new particles are created.

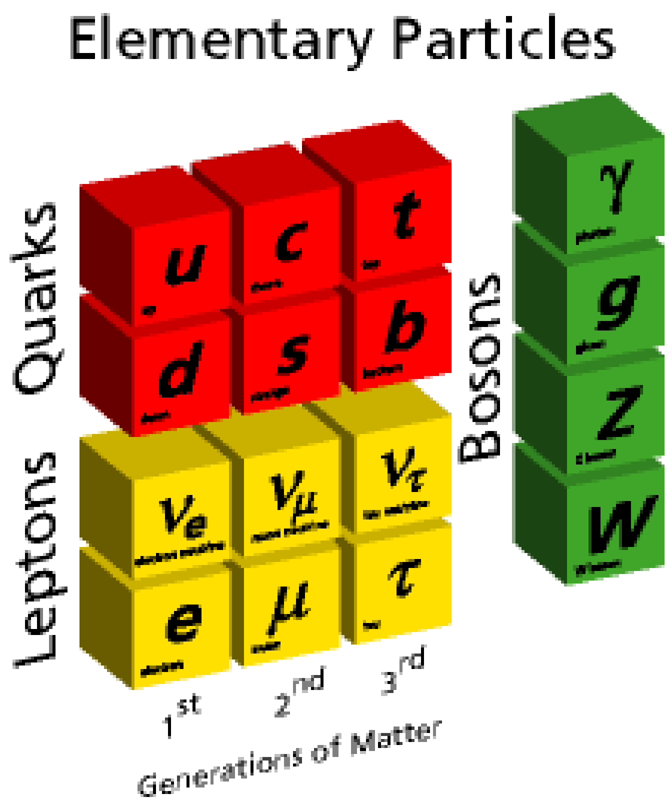
The SLAC National Accelerator Lab in California can propel particles a straight 2 mi (3.2 km).

The CERN Particle Accelerator presented in this video is the world's largest and most powerful particle accelerator and can boost subatomic particles to energy levels that simulate conditions in the stars and in the early history of the universe before stars formed **(2e)**: http://www.youtube.com/watch?v=sxAxV7g3yf8 (6:16).

The particles created in the accelerators were predicted mathematically. You probably already know about the parts of an atom, the protons, neutrons, and electrons. The protons and neutrons are made of smaller things, called **quarks**, while the electron is as far as we know, indivisible. The amazing results from the particle accelerators showed that protons and neutrons can be smashed apart at high enough energies, and other particles can be created from these collisions.

From these mathematical predictions and experiments physicists developed the **Standard Model**. It explains all the particles in our universe are based on several elementary particles held together by the four forces.

You know about the force of gravity. You may even understand electricity and light and magnetism, combined as the electromagnetic force. The standard model includes these two forces, as well as the weak nuclear force, and the strong nuclear force. The **weak nuclear force** is related to radiation, and the **strong nuclear force** holds quarks together in protons and neutrons.



Of these elementary particles, you experience the **photons**() of light energy every day. You experience electrons (e), and indirectly experience the **up quark** (u) and **down quark** (d) held together by **gluons** (g), all as part of atoms. The other elementary particles are only sensed in high energy particle accelerator collisions, and last for an incredibly short amount of time. The **neutrino** (v) is a type of particle that doesn't interact with matter like us, and there are many going through your body every second from the fusion in the sun and from distant stars.

5.2 Physics in a Nutshell from the Fermilab:

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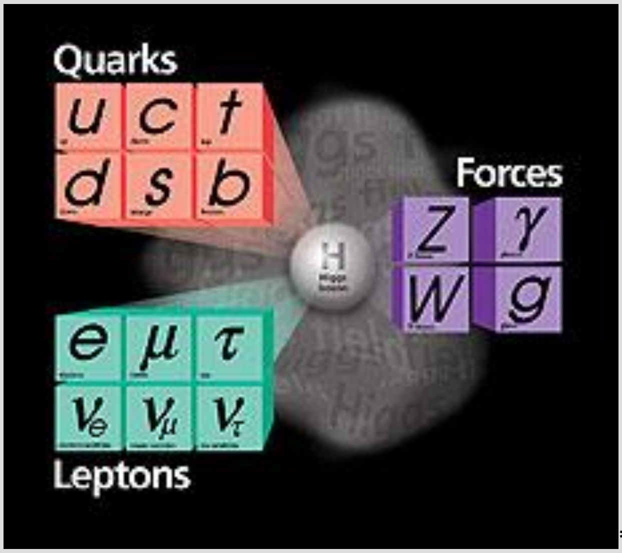
The Standard Model: The most successful theory ever



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The Standard Model is a triumph of modern physics. With this handful of particles shown here, we can explain all of the matter we have encountered, from atoms to entire galaxies.

The Standard Model. It's really a peculiar phrase. What's a model and what makes it standard?

In a physics context, the word "model" is analogous to the word "theory" as used by most people. We need to distinguish what actually happens when subatomic particles interact from our understanding of them. Hopefully, they're the same, but this is never guaranteed. The history of science is full of explanatory ideas that eventually were overthrown.

So what scientists do is construct what we call models, which are conceptual and mathematical ideas that explain our data. Once we have a model, we can use the tools of logic and math to make predictions. We then make additional measurements, and if they agree with the predictions of the model, we feel justified in continuing to believe the model is an accurate description of reality.

The model that we use to describe our subatomic reality is called "standard" because it is essentially universally accepted. After tens of thousands of measurements, the model continues to agree with the outcome of our research.

The standard model contains 12 particles that are the smallest building blocks we've ever found. These particles are broken into two classes: quarks and leptons. There are six quarks, oddly named up, down, charm, strange, top and bottom. Up and down quarks are found at the center of atoms, housed inside the familiar protons and neutrons, while the other four quarks are only found inside the collisions of particle accelerators.

Out of the leptons, the most familiar is the electron that makes up the outer layer of atoms. There are two other charged leptons, called a muon and a tau, which also are found only in particle accelerators and in cosmic rays from space. There are also some electrically neutral leptons called neutrinos. Neutrinos originate in nuclear reactions and we live in a bath of them from the sun. Since neutrinos only experience the weak nuclear force, they rarely interact. In fact, it takes about five light years of solid lead to have a fifty percent chance of stopping a neutrino from the Sun.

In addition to the particles, the Standard Model includes three forces that govern the behavior of matter. These forces are electromagnetism and the strong and weak nuclear forces. The familiar force of gravity is currently not included in the standard model. We understand the subatomic forces in terms of two matter particles exchanging force particles, like two kids tossing a baseball back and forth. The force particles are the photon (electromagnetism), the gluon (strong nuclear force) and the W & Z bosons (the weak force).

With these 12 matter particles and 4 force-carrying particles, we can explain the outcomes of all of our experimental data. We even understand, in principle, how to take these building blocks and reconstruct an entire universe.

The Standard Model is known to be incomplete and it doesn't answer all questions. However, it is a marvelous intellectual achievement and we expect that measurements taken at particle physics laboratories spread across the globe will continue to improve our understanding of the universe. These new insights will be incorporated into a new and improved Standard Model.
—Don Lincoln, Fermilab

The atom splashers

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In some Civil War battles, the shooting was dense enough and prolonged enough for bullets to collide. The atoms of the metal bullets redistributed themselves as a liquid, much like the quarks and gluons of heavy ion collisions.*Image source: brotherswar.com*

In most particle physics experiments, physicists attempt to concentrate as much energy as possible into a point of space. This allows the formation of new, exotic particles like Higgs bosons that reveal the basic workings of the universe. Other collider experiments have a different goal: to spread the energy among enough particles to make a continuous medium, a droplet of fluid millions of times hotter than the center of the sun.

The latter studies, often referred to as heavy-ion physics, require collisions of large nuclei, such as gold or lead, to produce amorphous splashes instead of point-like collisions. Lead ions, for instance, contain 208 protons and neutrons. When two lead ions hit each other squarely head-on in the Large Hadron Collider (LHC), many of the 416 protons and neutrons are involved in the collision, unlike the single-proton-on-single-proton collisions used to search for the Higgs boson. With so many collisions in such close proximity, the debris of the nuclei mingles and re-collides with itself like atoms in a liquid. Instead of just splitting in half, the nuclei literally melt.

This is a bit like what happens when two bullets collide in mid-air. Immediately after impact, the atoms in the bullets have enough energy to temporarily melt. Similarly, the quarks and gluons in the colliding lead nuclei spread and mingle as a droplet of fluid before evaporating into thousands of semi-stable particles.

This short-lived state of quark matter is unlike any other known to science. All other liquids, gases, gels and plasmas are governed by forces that weaken with distance. Water, for instance, is made of molecules that electromagnetically attract each other and repel oil. Clouds of interstellar dust are gathered by gravity and congealed by electromagnetism. In contrast, the quarks and gluons loosed by a heavy-ion collision are attracted to one another by the nuclear strong force, which does not weaken with distance. As two quarks start to separate from each other, new pairs of quarks and antiquarks join the mix with an attraction of their own.

This difference in the strong force law leads to surprising effects in the droplet as a whole. Experiments indicate that it is dense and strongly interacting, but with zero or almost no viscosity. As a result, it splashes through itself without friction. This differs from colliding bullets, which behave like clay because of the viscosity of liquid metal.

Quark matter is the stuff the big bang was made of. In the first microseconds of the universe, all matter was a freely flowing quark-gluon soup, which later evaporated into the protons and neutrons that we know today. Yet it is far from understood. It can only be produced in collisions and it is so short-lived that its properties have to be inferred from patterns in the particles that spatter away. Heavy-ion collisions in the LHC and RHIC at Brookhaven will tell us more about the origin of our universe.

—Jim Pivarski, Fermilab

Sacks and boats: subatomic forces

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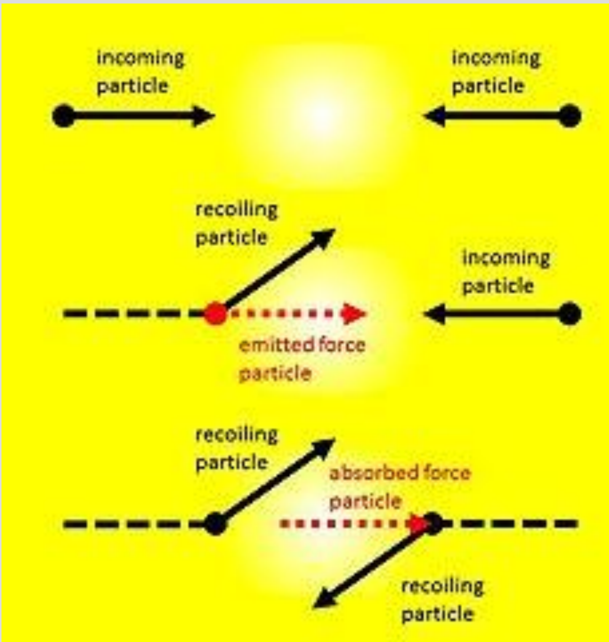
At the subatomic level, forces appear because one matter particle emits a force particle. When you throw a heavy sack off a boat, the boat recoils. Similarly, when one particle emits another one, the original particle recoils (moves). This is fundamentally how forces work at the subatomic level. Image courtesy of Dan Claes

Particle physicists explore the subatomic realm, which consists of quarks, leptons and the four forces that govern them. These forces are the strong nuclear force, the electromagnetic force, the weak nuclear force and gravitational force.

Here we'll look at some commonalities to understand what particle physicists mean when they use the term "force" and what we know about how these forces behave in the microworld.

The word force has a technical meaning in an introductory physics class. According to Newton's laws, a force changes the velocity of an object. Hitting the accelerator or brake pedal in your car will cause it to speed up or slow down. Each of these two actions, therefore, applies a force to the car. You can also change the velocity by changing direction. By turning the steering wheel of your car, you can make the car move left or right through the force between the tires and the road.

However, in everyday usage, the term force refers to something that can bring about change not just in velocity, but in general. An example is a military force toppling a government, inducing a change in the country's politics. When describing the forces between subatomic particles, particle physicists use a more general meaning like this one. While forces can certainly alter the trajectory of a particle or change its energy, they can also cause particles to combine, decay or change their identities. Thanks to subatomic forces, a photon can disappear and an electron and antimatter electron can appear in its place. In the subatomic world, forces induce many kinds of change.



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In a particle collision, two particles approach one another (top). The collision begins when one of the particles emits a force-carrying particle and then recoils (middle). The collision is complete when the second particle absorbs the force-carrying particle and also recoils (bottom). Note that the actual process whereby this occurs requires some quantum insights and is more subtle than this. However, this simplified version illustrates the most important points.

A class of theories called quantum field theories, or QFTs for short, describes the way that forces are induced in particle collisions. A basic property of these theories is that they replace the force fields of classical physics with quantum fields. For instance, in the quantum field formulation, Earth's gravitational field is treated as having lots of tiny force-carrying particles buzzing around. By way of analogy, think of air. We know what air is like—it's everywhere. However, we also know of air molecules, which can be considered quanta of air. The QFT approach focuses on the "atoms" of the force.

The scattering of subatomic particles can be calculated using the QFT formalism. Take the simple case of scattering two electrons. In the classical approach, the two electrons feel a repulsive force due to their respective electric fields. However, in the QFT approach, the force is caused by the exchange of a force-carrying particle. In this example, the force-carrying particle is a photon: one electron emits a photon, which is absorbed by the other one.

To understand how this works, imagine two people standing in nearby rowboats. If one person throws a heavy sack from one boat toward the other person, the throwing person's boat will recoil. If the second person catches the sack, that boat will also move. Because of the exchange of the sack from one boat to the other, the two boats will move away from one another. This action is the fundamental origin of the separating force between the two boats. In the same way, the exchange of a force-carrying particle can scatter two matter particles in a collision.

We can extend this analogy to other changes. For instance, the individual throwing the sack could also toss a yellow raincoat or a silly hat to the other person, so transferring these properties to the other. It is even possible to use this analog to explain attractive forces, although this stretches the boat analogy a little bit. In the following weeks, we will discuss how these ideas of particle exchange apply to the four known forces.

—Don Lincoln*, Fermilab*

Electromagnetism, the simplest force

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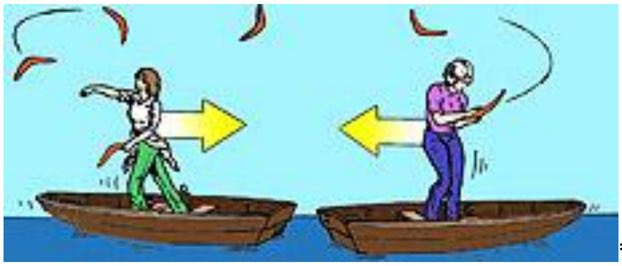
Much like the game of go, the basic rules of the electromagnetic force are simple, yet they play out in complex ways.

Electromagnetism is the training ground for modern physics, both in its historical development and in classrooms today. It is the simplest of the four forces, compared to the nuclear weak force, nuclear strong force and gravitation, but it gives rise to intricately rich patterns. All of the complex phenomena of everyday life, except for gravity and radioactivity, are due to the workings of electromagnetism. It makes chemical bonds, forming the basis of life, gives structure to solid and liquid matter, and makes lightning and aurora borealis twist across the sky.

And yet the fundamental rules of electromagnetism are startlingly simple: Like charges repel and opposite charges attract. If fundamental forces were board games, electromagnetism would be go, in which the rules can be learned in a few minutes but for which the strategy takes a lifetime to master. The other forces are more like chess, with more complicated fundamental interactions. The only problem with this analogy is that electromagnetism took physicists two centuries to learn and has never been mastered.

Electromagnetism was the first of the forces to be understood in a quantum context, in the late 1940s. The key insight was understanding that like charges repel because one emits a virtual photon and the other catches it, as described in the last Nutshell Sacks and boats: subatomic forces. Analogous to people in rowboats tossing a sack of flour back and forth, the momentum of the exchanged photons is transferred to the charges, pushing them apart.

So how do opposite charges attract? How can one boatman throw a sack of flour to another and have the boats drift toward each other? As it turns out, the quantum nature of the photon is essential. Photons can carry momentum without moving in a straight line between the throw and the catch: They pop from one location to another randomly. When two opposite charges attract, it is as though the sack of flour pops into existence behind the second boatman, pushing him toward the first. Think about that the next time two socks electrically cling in the laundry.

*

The attraction between opposite charges is a bit like two boaters tossing boomerangs, rather than sacks of flour. The photon appears behind the second charged particle, pushing it toward the first. *Image courtesy of Dan Claes*

You may have heard of photons as "particles of light." That's true, too. Photons can be found in a virtual state, in which they act as described above, or a real one. Real photons are massless quanta of light, radio, gamma rays and any other frequency of electromagnetic radiation. Virtual photons are sometimes massive, sometimes here, sometimes there, always flitting back and forth between charges to bring them together or push them apart. Moreover, "virtualness" or "realness" is a matter of degree—visible light only approximates a massless train of waves.

The one aspect of electromagnetism that makes it seem simple (in comparison) is the fact that photons themselves do not attract or repel each other; they only affect charged particles. This feature separates electromagnetism from all the other forces. Strong force gluons are a sticky mess of gluons attracting gluons by emitting gluons, weak force dynamics are complicated by self-couplings, and gravity can attract itself in the form of a black hole. But the surprising thing is that the two nuclear forces look a lot like electromagnetism—they follow the same paradigm of virtual particles being tossed back and forth. They differ only in the details of how the pieces interact as they move across the board.

—Jim Pivarski, *Fermilab*

The gluon and the strong nuclear force

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The strong nuclear force holds together the protons and neutrons in the nucleus of an atom. This is actually a side effect of its function binding quarks together to make the protons and neutrons themselves. The particle of the strong force is called the gluon because of the strong force's glue-like properties.

The strongest of the subatomic forces is the aptly named strong nuclear force. In the realm in which it operates, it is about 100 times stronger than the next-strongest force (electromagnetism). But it isn't just its strength that distinguishes it from the other forces. It has other properties that differ from, for instance, the features of a magnet. The force between two magnets extends over a long distance and becomes stronger as the magnets are brought closer to one another. In contrast, the strong nuclear force is a lot more like glue. If you have two marbles made sticky by some kind of adhesive, they will cling together when they are made to touch each other. However, once the two marbles are separated by even a very small distance, they no longer feel any attractive force at all.

In homage to the force's commonalities with how glue behaves, the force-carrying particle for the strong force is called the gluon. Gluons are responsible for binding protons and neutrons together inside the nucleus of an atom. This is crucial for building atoms, but this nuclear binding is actually a side effect of what the gluon really does—hold together the quarks that make up protons and neutrons. In high-energy physics experiments, it is the quark-quark binding that is of the greatest interest.

The distance over which the nuclear force is active is about 1 femtometer (10^{-15} or one quadrillionth of a meter). To give an idea of just how mind-bogglingly small that is, if a proton were as thick as a sheet of paper, by comparison you'd be so big that, if you stood on the Earth, your head would touch the Sun.

In the last Nutshell "Electromagnetism, the simplest force," we were introduced to the photon, the quantum of the electromagnetic force. Because the photon is electrically neutral—that is, it has no electric charge—photons don't interact with each other. In contrast, every gluon has a strong nuclear charge. Thus gluons interact not only with quarks, but also with other gluons. This gluon self-interaction property is one of the reasons that the strong force acts like glue instead of magnets.

The charge of the nuclear strong force is known as color. In a subatomic context, three colors—red, blue and green—are carried by the three quarks in a proton, resulting in a simple color scheme. In contrast, the force-carrying gluons have a rather complex color palette, one with a mix of both color (the charge carried by quarks) and anticolor (the charge carried by antiquarks). In total, there are eight different color combinations that gluons can carry. (If you're wondering why three colors and three anticolors combine to make eight gluons and not nine, the answer can be found here.)

Gluons were discovered at the German laboratory DESY in the late 1970s. They play a key role in many of the studies performed at the Tevatron and the LHC.

—Don Lincoln

The weak world


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Like electromagnetism and the strong force, the weak force transfers momentum by tossing an intermediate boson. However, the act of throwing or catching the boson also transforms the particles.

Of the four fundamental forces, the weak force is the most mysterious. It is the only one with no obvious role in the world we know: The strong force builds protons and nuclei, electromagnetism is responsible for nearly every macroscopic phenomenon, and gravity, though weaker than the rest, is noticeable because of our close proximity to a reasonably large planet.

The only observable phenomenon due to the weak force is the radioactivity of certain substances (not all). I sometimes wonder if this major aspect of nature might have gone unnoticed if Henri Becquerel hadn't kept his unexposed photographic film and his uranium samples in the same drawer. Early 20th-century physicists wondered why some rocks emit strange rays—it turns out that there's a new force that transforms particles so that they are no longer bound to the nucleus. Mid-20th-century physicists wondered why this force is so weak—it turns out that its intermediary force carrier, its analog of the photon in electromagnetism, is very massive and therefore rarely produced. Physicists today wonder why the weak force carrier is so massive—it may be that there's an omnipresent Higgs field binding to it, slowing it down and giving it effective mass. The particulate form of that Higgs field may have been discovered last year, at long last.

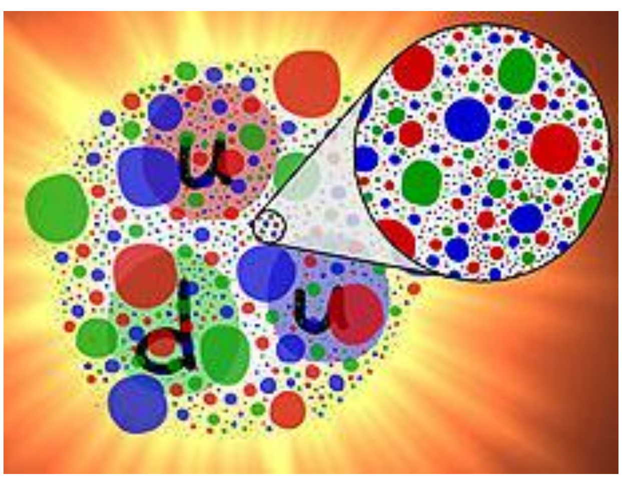
The weak force is the most eclectic of the four—it violates most of the conservation rules that the others uphold. The strong force, electromagnetism and gravity all act on antimatter the same way with the same strength as on equivalent samples of ordinary matter; the weak force does not. The same is true of mirror-flipped and time-reversed configurations; the weak force uniquely distinguishes between clockwise and counter-clockwise, between forward and backward.

In fact, interactions through the weak force change the identity of all particles involved. In previous articles, we showed how forces push and pull by exchanging an intermediary. In the case of electromagnetism, two charged particles repel by throwing a photon from one to the other, like a heavy sack thrown between two boats. For the weak force, this is either a charged *W* boson or a neutral *Z* boson. When a quark emits a *W* boson, however, it becomes a new type of quark. Charmed quarks turn into strange quarks, and muons become electrons. In addition to carrying the momentum of the force, the *W* boson takes some of the strangeness or the charmness out of one quark and into another.

In its unique role as rule-breaker, the weak force may be responsible for the matter-antimatter asymmetry in the universe. Its weakness may be hiding dark matter. The weak force seems to be tied to so many fundamental mysteries, it's amusing to think that the whole thing might have been overlooked if Victorian physicists hadn't been so curious about strangely warm rocks.

—Jim Pivarski, Fermilab

Quarks and gluons and partons, oh my…

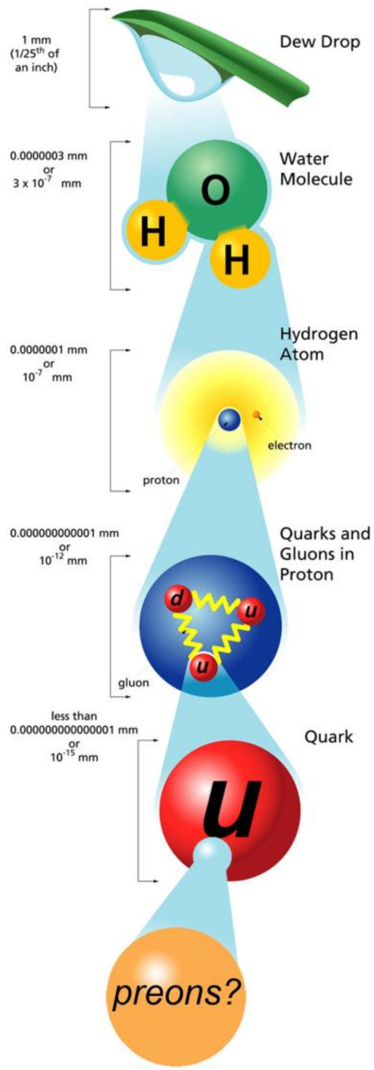


The proton consists of a complex mixture of quarks and gluons. Physicists use the word parton to describe all constituents of a proton.

When physicists talk about what is found inside a proton, they toss around many words. Quarks, gluons and partons are the most common ones. So what do they mean?
First we need to remember that a proton is a subatomic particle that can be visualized as a sphere about 10^{-15} meters across. That means they're as small compared to a virus as a virus is compared to you. When you consider that many viruses are so small that they can't be seen in the best microscope, you get a sense of just how small a proton is. The proton also has the same electric charge as an electron, but it is a positive charge rather than a negative one. We call the charge of a proton +1.
In the 1950s it became increasingly clear that the proton must consist of smaller particles. If the proton can be compared to a beanbag, the obvious question is: What do we know about the beans? In 1964, Murray Gell-Mann and George Zweig independently proposed that the proton (and also the neutron) consisted of three smaller particles. We now use Gell-Mann's name for them: quarks. While we now know of six types of quarks, the original theory only proposed three: up, down and strange. Quarks also have electrical charge, with the up quark having +2/3, while the down and strange quarks both have -1/3. Protons consist of two up quarks and a down quark, while neutrons consist of two down quarks and an up quark.
When quarks were proposed, they were still theoretical. They needed experimental confirmation. In 1968 at SLAC, experiments using electrons to probe the structure of the proton demonstrated clearly that protons contained within them smaller objects; the beans in the beanbag had been observed. However initially it was impossible to show that these proton constituents were quarks. Richard Feynman called them partons, as they were part of the proton.
Attempts to understand exactly that bound the partons inside the proton led to the generation of the current theory of strong force interactions, called quantum chromodynamics, or QCD. This theory postulated that there would be additional particles in the proton called gluons. In order to explain the measurements, these gluons would interact a different type of charge, called color, associated with the strong force. Gluons were observed at the HERA accelerator in Germany in 1979.
Subsequent experimentation has definitively shown that protons consist of both quarks and gluons. The term parton now means any particle inside a proton, neutron or other quark-containing particle. By far, quarks and gluons are the most common partons.
While up, down and strange quarks were components of the original model, we have since found three others, called charm, bottom and top. Both the bottom and top quarks were discovered at Fermilab. Studies at the Tevatron and now the LHC have searched for additional quarks, but these studies have thus far been unsuccessful.
—Don Lincoln, Fermilab

And so, ad infinitum: Smallest of the small

Scientists are searching for particles smaller than the familiar ones of the Standard Model.



Big fleas have little fleas, Upon their backs to bite 'em, And little fleas have lesser fleas, and so, ad infinitum. — Augustus De Morgan

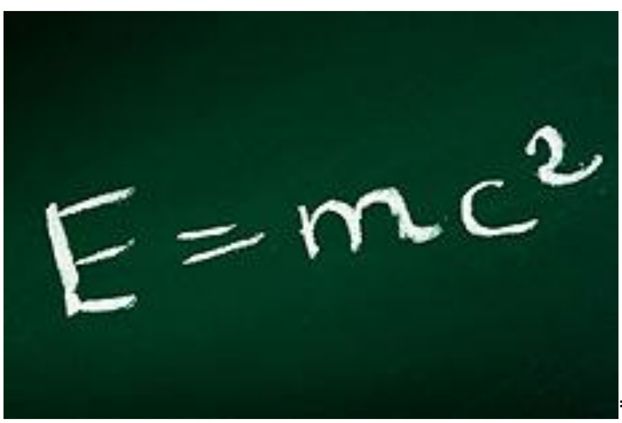
Suppose you were the size of the universe - you would see a bunch of luminous, point-like dots surrounding you. If you shrank, you'd identify these points as galaxies, each with a rich structure and each filled with a new bunch of point-like dots. As you shrink more, you'd see that these new dots were not points, but stars.

If you pressed the supershrink button on your shrink ray, you'd zoom down through the size of humans, through cells, molecules, atoms, atomic nuclei, protons and neutrons and finally down to the size of the quarks and leptons that constitute the knowledge frontier of the super small. Over the past hundred years or so, a series of objects like atoms were thought to be the smallest building block of matter, only to have subsequent research show that we were wrong.

The Standard Model exemplifies the micro world of particle physics. Two classes of particles, called quarks and leptons, are thought to be the smallest building blocks of the universe. They have no size and contain nothing in them, but, if mixed correctly, they can build atoms, us, the entire universe.

After about a century of progressively finding something smaller than what we thought was the smallest, why should anyone think that these quarks and leptons are the final word? The answer is complex.
At the experimental level, the answer is unequivocal. There is precisely zero evidence that quarks and leptons have any size at all. Physicists at Fermilab's Tevatron and CERN's LEP and LHC colliders have set a limit on the size of quarks and leptons, which is that they must be smaller than about 0.001 times the size of a proton. The sensitivity of the detectors would let us see quarks and leptons if they were larger than that, so we know they must be smaller.
On the flip side of the argument, the Standard Model offers an explanation for the possibility that quarks and leptons have an internal structure. Ordinary matter is made of up and down quarks (found inside protons and neutrons) and electrons. The charm and top quarks seem to be heavier carbon copies of the up quark. Similarly, the strange and bottom quarks are clones of the down quark, while the muon and tau lepton are heavier cousins of the electron. This repetitive structure is reminiscent of the periodic table of chemical elements, in which the columns of chemically similar elements were the first signs that the atoms weren't point-like. Maybe the heavier copies of the quarks and leptons signal the next level in the subatomic onion.
Theoretical physicists are aware of these possibilities and have written hundreds of papers describing hypothetical particles as the building blocks of quarks and leptons. The names suggested for these proposed particles include subquarks, maons, alphons, quinks, quips, rishons, tweedles, helons, haplons and Y-particles. The most common, generic term physicists use is preons.
The LHC and Fermilab's Intensity Frontier experimental program are ideal methods for looking for direct evidence for preons. The first approach is brute force – we smash the quarks and leptons together to see how they behave. If the collisions act point-like, the quarks and leptons might have zero size, or at least be smaller than we can measure.. The second approach looks for very rare processes, including muons decaying into electrons and photons or to measure the spin of a muon (technically the magnetic moment), to see if they have non-zero size.
The search for the ultimate building blocks of matter is an old quest, begun anew with each advance in accelerator and detectors. The recent and near future improvements in particle physics instrumentation makes this an exciting time for those of us searching for the smallest of the small.
—Don Lincoln, Fermilab

$E = mc^2$



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Einstein's equation is the most famous one of modern physics; however, it never appeared in his first paper. Instead his paper included the unwieldy but equivalent, $K_0 - K_1 = (L/c^2) \times (v^2/2)$.

Einstein's equation is the most famous equation in history. Even people who have absolutely no interest in science recognize it. But what does it mean?

Well, like all equations, it has a left side and a right side, separated by an equal sign. On the left-hand side is "E," which means energy. On the right-hand side is "m," which means mass, and "c," which means the speed of light.

The speed of light is simply a mathematical constant that converts units of energy to units of mass, similar to the conversion factor you'd use to translate feet to inches. In the middle is the equal sign, which just says that the right hand and left hand side are the same. Stated simply, this equation says that energy and mass are the same once you apply the c^2 conversion factor to get the numbers right.

That last sentence is such an unassuming one, yet it has huge implications. If two things are the same, you can convert one into another. Scientists who use accelerators like those at Fermilab, CERN and other similar laboratories make this conversion all the time. We accelerate particles to high energies and slam them together. The particles' kinetic (motion) energy can convert into mass energy. This is how particles like the top quark and the Higgs boson are made.

It's important to note that the "m" stands for "mass," not matter. When we convert energy into mass, we do in fact convert the energy into matter, but we also simultaneously convert it into antimatter. Of course, the equal sign in the equation means the conversion can go both ways: You can combine matter and antimatter to make energy. This is the basis for the Dan Brown book *Angels and Demons*, in which a scientist isolated a quarter gram of antimatter. If that were technologically possible, Brown's story would be feasible. Combining a quarter gram of antimatter and matter would result in an energy release similar to those from the first atomic bombs. Luckily for mankind's safety, it is difficult to isolate antimatter. Fermilab's antiproton source was the world's most powerful facility for making antimatter, and yet 25 years of effort isolated only enough antimatter to warm five gallons of water from room temperature to the temperature of a decent cup of coffee.

One aspect of this equation is kind of mind-blowing. Consider ordinary matter of the kind that makes up you and me. We are made of atoms, which are made, in turn, of protons, neutrons and electrons. Electrons are far less massive than protons and neutrons. Protons and neutrons have similar masses, so we can conceptually combine them as a class of particles called nucleons, indicating their location in the nucleus of an atom. Thus most of your mass comes from the various nucleons in your body.

Things get really interesting when we ask where the nucleons' mass comes from. Each nucleon consists of three quarks, so the obvious answer is that each of the quarks carries about a third of the mass of a proton. However, that's not true. The mass of the quarks is only about 1 to 2 percent the mass of the proton. So where does the mass of the proton come from? Energy.

Inside a nucleon, the quarks are zooming around at speeds near that of light. This gives them a lot of kinetic energy. In addition, they are zooming around in a volume the size of a sphere a quadrillionth (10^{-15}) of a meter in radius. To have something moving that fast in a volume that small requires very strong forces to hold them together. This requires a lot of potential (binding) energy. The combined kinetic and potential energy is the real source of a person's mass.

In essence, there is very little mass in the way we intuitively understand it. Everything is energy. Einstein's equation, first invented over a century ago, showed us a central truth of the universe. Matter is energy.

—*Don Lincoln, Fermilab*

Lesson Summary

- Protons and neutrons can be smashed, and are made of quarks held together by gluons.
- Elementary particles include quarks, leptons (electrons and others), and bosons (force carriers)
- The four forces are gravitational, electromagnetic, strong nuclear, and weak nuclear.
- The Standard Model describes the rules of the entire universe.
- The Standard Model includes the elementary particles and the four forces.

Review Questions

1. What kind of elementary particle is an electron?
2. What are the components of a proton or a neutron?
3. Name the four forces in the Standard Model.
4. What force keeps a proton or a neutron together, and what boson (force carrier) holds quarks together?
5. What force is the electron associated with?
6. How small is a quark?
7. Name some particle accelerators where these particle physics discoveries have been made.
8. How many up and down quarks in a proton? In a neutron?

Further Reading / Supplemental Links

- Videos summarizing particle physics http://www.youtube.com/watch?v=V0KjXsGRvoA http://www.youtube.com/watch?v=XYcw8nV_GTs
- More about the standard model: http://physics.info/standard http://www.particleadventure.org/standard_model.html
- look for material from scientific organizations, universities, and laboratories, such as Fermilab, SLAC, CERN, Quarknet.

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