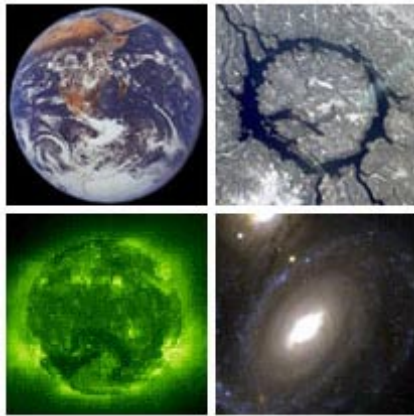


Earth in Space



Introduction
Origin of the Universe
The Solar System
The Earth & Sun
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Impact Hazards
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Summary

We travel together, passengers on a little space ship, dependent on its vulnerable reserves of air and soil; all committed for our safety to its security and peace; preserved from annihilation only by the care, the work, and, I will say, the love we give our fragile craft.

Adlai Stevenson

We have only one planet. If we screw it up, we have no place to go.

J. Bennett Johnston

Introduction

- Ancient civilizations believed in a geocentric universe in which the Sun revolved around Earth.
- Early astronomers such as Copernicus, Kepler, and Galileo advanced the concept of a heliocentric universe with the Sun at its center.
- Our home planet has a unique position in our solar system, providing us with liquid water and sufficient heat energy to sustain life.
- Geological processes on Earth are driven by energy from the interior of the planet or from solar radiation.
- The future of life on Earth is threatened by a collision with near-Earth objects such as asteroids and comets.

Earth's Orbit

Ancient civilizations observed the Sun rising in the east and setting in the west and inferred that the Sun revolved around Earth in a **geocentric** (Earth-centered) orbit. The Greek philosopher **Aristotle** believed Earth was at the center of the universe and that the visible planets (Mercury, Venus, Mars, Jupiter, Saturn) and stars revolved around the Earth.

Aristarchus, another Greek philosopher, calculated the relative size of Earth and the Sun and concluded that it was more probable that Earth revolved around the massive Sun in a **heliocentric** (Sun-centered) orbit. However, his interpretation would go unheeded for nearly 1800 years.

The geocentric model became increasingly complex nearly five centuries after Aristotle to account for more-detailed

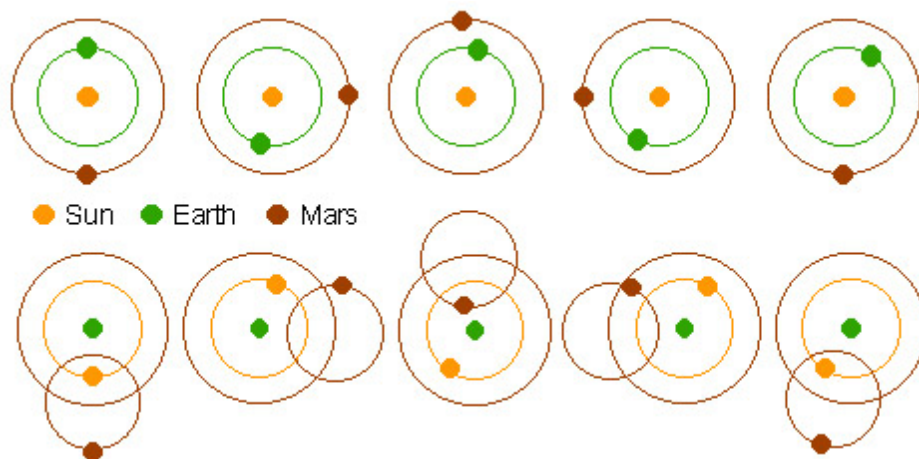


Figure 1. Relative positions of Sun, Earth, and Mars in models of heliocentric (top) and geocentric (bottom) orbits. Earth and Mars both orbit the Sun in the heliocentric model. Earth makes nearly two orbits of the Sun during a single Mars orbit. The geocentric model required that Mars followed a path that described a small circle as it revolved around Earth.

observations of planetary motion. **Ptolemy** updated Aristotle's work to account for apparent reversals in the orbits of the visible planets. The new model concluded that planets orbited Earth along circular paths but would also follow a route around a smaller circle (Fig. 1). The Ptolemaic system was accepted without any serious challenge for over a thousand years but additional celestial observations required that the geocentric system be further modified, making it increasingly complex and unwieldy.



Figure 2. View of Earth from the Moon by Apollo 8, the first manned craft to orbit the Moon, December, 1968. Image courtesy of NASA

Nicolaus Copernicus (1473-1543) became an advocate for the heliocentric universe in the sixteenth century. Copernicus inferred that the planets revolved around the Sun in circular orbits and determined the relative distance of the planets from the Sun based on their reversals of motion. In addition, he recognized that Earth must spin on its axis once per day. Although his reinterpretation of the known solar system was able to simplify some of the complexity of the Ptolemaic system, Copernicus still had the planets describing secondary orbits along small circles and was unable to offer any unassailable proof that the heliocentric view was superior to the geocentric interpretation. Copernicus published his ideas in his book, *On the Revolutions of the Heavenly Orbs*, in 1543.

About a century later, German astronomer **Johannes Kepler** (1571-1630) modified the ideas of Copernicus to conform to more-detailed observations. Kepler discovered that the planets had elliptical, not circular, orbits and that the speed of planetary motion decreased with distance from the Sun. Kepler was the first astronomer to calculate the length of time it would take for planets to complete an orbit. Italian mathematician **Galileo Galilei** (1564-1642), a contemporary of Kepler, introduced technology into cosmic exploration when he built an early telescope in 1609. Galilei used his telescope to make the first observations of the cratered landforms on the Moon's surface, the larger moons of Jupiter, and the phases of Venus (changes in the appearance of the planet as it orbited the Sun). Kepler's ideas coupled with Galileo's observations were sufficient to convince skeptics that the heliocentric system accurately portrayed the relative motions of the sun and planets. Finally, **Isaac Newton** discovered the force that held the planets in their orbits around the sun - **gravity**. He formulated one of the universal laws of nature, the law of gravitation, "*every body in the universe attracts every other body.*"

Earth in Space

Although we were able to explain Earth's position in space, the unique nature of our planet was not driven home until we were able to look at our home from the outside. The astronauts aboard the Apollo 8 spacecraft were the first to glimpse our home planet from space (Fig. 2). While orbiting the Moon on Christmas Eve 1968, the crew read the first 10 verses of Genesis during a broadcast to Earth. At the end of the reading Frank Borman closed communications with ". . . *Merry Christmas, and God bless all of you, all of you on the good earth*". For many back home, those early views of the planet from the inky darkness of space illustrated the unique wonders of the fragile environment we share on spaceship Earth. In this chapter we seek to introduce you to the reasons why that natural environment exists and to a potential threat to its future. The chapter is divided into six sections; the first three examine Earth's position in space and the remainder discuss the potential hazards associated with the collision of an asteroid with Earth.

The **Origin of the Universe** takes us on a journey through time and space to examine how scientists think the universe began and to explore some of the far corners of the Cosmos. We will place Earth and the Sun in the context of the much larger universe and learn if there are other systems of planets and stars out there that might harbor life. We follow that with a closer look at our own **Solar System** where we compare Earth to our neighboring planets. We exist because our home, this good Earth, is perched 150 million kilometers from the Sun, close enough to have liquid water to sustain life, and far enough away to moderate the Sun's heat (Fig. 3). The solar system examines the fortunate set of conditions that makes life on our home planet possible while our nearest neighbors orbit the Sun as barren rocks. The geological processes that operate on Earth draw their energy from the decay of radioactive materials in the interior of the planet and from solar radiation absorbed on or near the surface. We take a closer look at the structure of Earth's interior in the section on the Solar System, while the **Earth & Sun** examines how the distribution of solar radiation on Earth's surface regulates the length and order of the seasons and provides the energy for the operation of the biosphere, hydrosphere, and atmosphere. We will also examine how the elements of the earth system are linked by cycles that transfer energy and resources between different parts of the system. The interaction of solar radiation with our atmosphere generates a beneficial greenhouse effect that has contributed to



Figure 3. Earth viewed from space. Image courtesy of NASA.

a flourishing biosphere. We will introduce the linkage between atmospheric composition, solar radiation, and global climate in this section.

Death from the Sky

\$100: Price Michelle Knapp paid her grandfather for her Malibu Classic

\$10,000: Selling price of Michelle's car following the meteorite impact

\$69,000: Selling price of the meteorite

A 12-year old red Chevrolet Malibu Classic would seem like an odd choice to appear in the American Museum of Natural History. The presence of the car seemed even more surprising when you noticed the gaping hole that passed from the trunk through the gas tank. However, it is this hole that gave this particular Malibu Classic its significance. The hole formed on a 1992 fall evening when a 12 kg (27 pound) meteorite smashed through the car and embedded itself in Marie Knapp's driveway in Peekskill, New York. The car belonged to her daughter Michelle and quickly became a scientific icon among the community of meteorite hunters willing to pay top dollar for these flying space rocks.

The Peekskill meteorite represents just one of thousands of objects that collide with Earth each year. Some are large enough to reach the surface of the planet relatively unscathed, but most of these cosmic visitors burn up harmlessly in the atmosphere. The second half of the chapter reviews the current state of knowledge about the potential for collision with such near-Earth objects (NEOs). Past impacts by large NEOs are thought to have resulted in a widespread extinction approximately 66 million years ago that wiped out the dinosaurs and a more recent explosion in the last century that felled 2,100 square kilometers (840 square miles) of Siberian forest. The section on **Near-Earth Objects** examines where these objects come from and discusses their potential for collision with Earth. The evidence for past impacts and the potential consequences of such an impact are discussed further in the **Impact Hazards** section. We will learn that NEOs routinely strike our planet and that approximately one impact per century has the potential to cause widespread destruction equivalent to a major natural hazard. The final section of the chapter, **Beware Flying Rocks**, considers what can be done to prevent the end of the world as we know it because of a collision with a NEO. We review efforts to track larger NEOs and discuss how we might cope with the discovery that a large rock has Earth in its crosshairs.

Think about it . . .

How is Earth's position in space experienced in our lives?

Origin of the Universe

- The universe is estimated to be approximately 15 billion years old based on estimates of the rate at which distant galaxies are moving away from us.
- Astronomers have created a model of the origin of the universe known as the Big Bang in which early galaxies formed from the accumulation of cosmic debris in giant molecular clouds.
- Stars formed when dense regions in these clouds collapsed inward and planets formed from the accretion of debris in the gravitational field of the stars.

We live on a small rocky planet that circles one of the hundreds of billions of stars in the Milky Way galaxy. The Milky Way is just one of tens of thousands of galaxies embedded in the much larger universe. Astronomers don't use conventional measures to determine the dimensions of objects in space because of the vast distances involved. Instead they use units known as **light years**, a measurement that represents the distance light would travel in a year, equivalent to 9,460 billion kilometers (5,870 billion miles). The Milky Way has a radius of 50,000 light years whereas the edge of the universe is approximately 15 billion light years away.

How Big Is the Universe?

Current estimates of the age, scale, and origin of the universe rely on our understanding of the relative motions of distant galaxies. Scientists have used the brightness of an unusual type of star and changes in the character of light to measure the size of the universe.

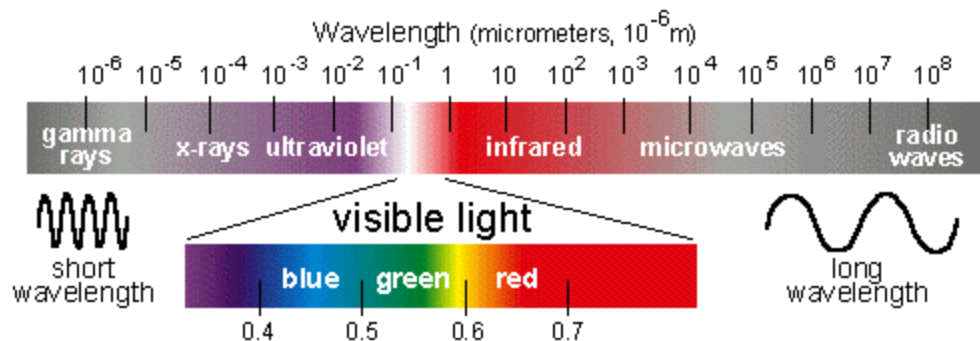
Astronomers have recognized a group of pulsating stars known as **cepheid variables** for nearly a century. Cepheids were first recognized in our own galaxy and it was learned that the brightness of these stars varies in a predictable pattern over a specific time interval. Scientists can determine a star's average luminosity simply by measuring the time between periods of maximum and minimum brightness. The average brightness is then used to calculate our distance from the star. Brightness decreases with increasing distance. The same principle would allow us to estimate distances between cars on a dark highway on the basis of the brightness of their headlights.

The first indication of the enormity of space came from measurements of the illumination from clusters of cepheid variables in deep space. It was soon realized that these stars were not part of our own galaxy but members of distant star fields. The timing of their pulsations revealed their actual brightness which was then compared to brightness values measured from Earth to determine their distance. More surprising still, by repeat measurements on several occasions, it was discovered that all of these star clusters were moving away from us. Astronomer Edwin Hubble noted that **the greater the distance to an object, the faster it was moving away from our galaxy**. He formulated a simple law that related the distance of a galaxy to the speed at which it was moving. The question then became: How far away is the most distant galaxy?

As technology improved, even more distant objects could be discerned but cepheid variables could not be recognized in these distant galaxies. However, the previous observations of the cepheids had laid the foundation for another technique that could be used to measure vast interstellar distances. Hubble noted that the wavelengths of radiation from distant cepheids were stretched, a phenomenon known as **red shift**. Different colors of visible light have normal wavelengths of 0.4 to 0.7 micrometers (1 micrometer = 0.000001 meters; Fig. 4). Violet and blue have the shortest wavelengths, red wavelengths are the longest.

Hubble noted that the wavelength of light from distant stars was consistently shifted toward the red end of the spectrum. The further away the star, the greater the red shift. He recognized that radiation from distant stars was subject to the **Doppler effect**, the compression of waves moving toward us and the stretching of waves moving away. We observe the

Figure 4. The electromagnetic spectrum. Radio waves can have wavelengths measured in hundreds of meters. In contrast, wavelengths for visible light are less than 0.0001 mm across but are a million times larger than the wavelength of gamma rays.





same phenomenon in the changing sound of a siren from a passing ambulance or fire truck. Sound waves are compressed as the vehicle approaches our location but the waves become elongated as the vehicle recedes into the distance. If we could gauge how quickly the sound changes we could estimate the speed at which the vehicle was moving. Astronomers applied the same principle to calculate the distance to the furthest galaxies by determining how much their radiation is shifted toward the red end of the spectrum. This distance measurement has the added benefit of having a time component that allows us to identify the age of objects. It takes one billion years to receive light from a star that is one billion light years away (Fig. 5). The presence of objects 15 billion light years distant indicates that the universe must be at least 15 billion years old.

Figure 5. Deep-field view of multiple galaxies and stars in a small section of the universe taken with the Hubble telescope. This view is a composite of nearly 300 images collected over a 10-day period in 1995. Visit the Space Telescope Science Institute (STScI) for more views from the Hubble Space Telescope. Image courtesy of STScI.

The Big Bang

Knowing that the most distant galaxies are moving away from us in all directions, astronomers simply reverse this process to step back in time to the beginning of the universe. By running the movie backward, it becomes clear that the universe must have been much smaller and more compact during its earliest stages. Compressing all matter into a small space would result in temperatures and pressures far beyond anything present in our solar system today. The universe is interpreted to have begun with a massive explosion, the **Big Bang**, that generated intense temperatures and pressures billions of times greater than conditions in the core of the Sun. The super-high temperatures prevented the formation of atoms but tiny clumps of positively charged protons and neutrons (no charge) were flung outward through space. Although the rate of expansion gradually slowed, space is still expanding today. After a couple of minutes temperatures declined sufficiently for atoms of the

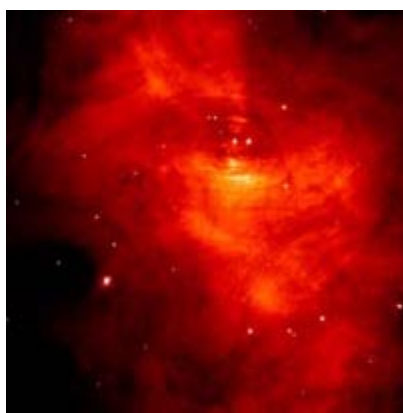


Figure 6. Top: Giant molecular cloud of gas and dust in the Eagle Nebula. Light from young hot stars are visible at the top of each pillar. Middle: Spiral galaxies like the one pictured above account for about a third of all galaxies. Young stars are located in the outer arms. Bottom: The Crab Nebula, the remnants of a supernova that occurred nearly a thousand years ago. Images courtesy of STScI.

first and simplest chemical elements, **hydrogen** and **helium**, to form. These elements still dominate space but through a series of reactions they will be combined to form the many common elements known on Earth.

Clumps of gas and dust, pulled together by gravitational attraction, began to form approximately 300,000 years after the formation of the universe. As these **giant molecular clouds** (Fig. 6) of cosmic debris grew they formed **proto-galaxies**. When they had achieved sufficient mass, dense regions in the clouds of gas and dust collapse inward, generating high temperatures and pressures. Fusion reactions occur in the cores of these bodies to form **stars**. The type of star formed varied with size ranging from massive, short-lived stars several times the size of our Sun to smaller, cooler Earth-size **red dwarf** stars. A star 10-times larger than the Sun would burn fiercely for 20 million years before collapsing in a **supernova** (Fig. 6), a massive explosion that would fuse together simple elements (hydrogen, helium) to more complex forms (carbon, oxygen, silicon).

The life cycle of big stars represents an elemental manufacturing plant, generating the complex compounds necessary for the formation of our planet and everything on it. Infrared satellites have detected over 70 different chemical compounds in giant molecular clouds including molecules of water, methane, and carbon dioxide. Intermediate stars such as our Sun burn less intensely, conserving their fuel for 10 billion years. We are approximately halfway through the Sun's life cycle. The final stage of the Sun will result in it expanding outward to form a **red giant** star, consuming Mercury in the process. By that time the increased temperatures will probably have caused Earth's oceans to have evaporated and the decreased mass of the expended Sun will result in an expanded orbit for Earth, sending it finally into the colder reaches of the solar system.

Primitive stars were surrounded by a disk of debris that became segregated into **planets**. Stellar winds from the outer edges of the star blasted lighter gases like hydrogen and helium to the outer, colder parts of the nascent planetary systems to form icy, gas-rich planets. The heavier elements collected closer to the star to form rocky planets. The consistent orbital directions for the planets around their stars is evidence that they all formed from the same swirling mass of gas and dust. A similar pattern

is revealed in the revolution of multiple moons around planets such as Jupiter and Saturn.

Astronomers have long recognized that most stars do not have orbiting planets but recent advances in technology and search methods have resulted in a surge in discoveries of previously unrecognized planets. Only recently have scientists discovered other planets orbiting some of our nearest neighbor stars.

Scientists currently recognize over 50 **extrasolar planets** that exist beyond our solar system. Current instruments can only detect relatively large planets that are approximately the size of Jupiter or larger. Surveys suggest that only 5% of sunlike stars have orbiting planets of this size. Many of the planets that have been identified are located much closer to their stars than Earth is to the Sun making them unlikely hosts for life.

Think about it . . .

Make a concept map of the components of the universe using the terms that follow. Generate your own linking phrases to connect these terms together.

universe	galaxies	stars	planets
Sun	red dwarf	red giant	Milky Way

The Solar System

- Earth is one of nine planets, their satellite moons, and thousands of asteroids in our solar system.
- The terrestrial planets are solid and composed of compositional layers whereas the larger Jovian planets are dominated by gases.
- The physical characteristics of Earth and its position relative to the Sun have resulted in a unique set of conditions that led to the development of a flourishing biosphere.
- Energy for internal earth processes is derived from heat from the planet's interior.

The Sun is the centerpoint of a system of nine planets (Fig. 7). In order, with increasing distance from the Sun the planets are: **Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto**. The planets are divided into two groups.

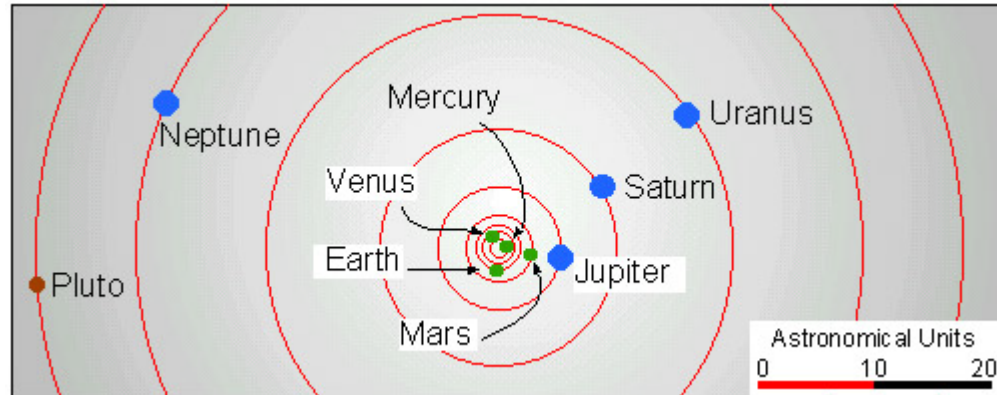


Figure 7. Relative positions of the planets in the solar system. Note the relative proximity of the terrestrial planets in comparison to the greater spacing between Jovian planets. One astronomical unit is the average distance from the Sun to Earth.

The group of smaller planets (Mercury, Venus, Earth, Mars) nearest the Sun share similar origins to Earth and are termed the **terrestrial planets**. The much larger outlying planets (Fig. 8), sometimes termed the gas giants, include Jupiter, Saturn, Neptune, and Uranus. These planets also share similar properties and are labeled the **Jovian planets** (Jupiter-like).

The average distance from the Sun to Earth represents one astronomical unit (AU; $1\text{AU} = 150\text{ million kilometers} = 94\text{ million miles}$). The planets range from 0.4 AU for Mercury to 39 AU for Pluto. The four innermost planets all lie within 1.5 AU of the Sun; essentially one planet per 0.4 AU. Mars, the farthest terrestrial planet, is separated from Jupiter, the nearest Jovian planet, by 3.7 AU. This gap houses the asteroid belt, thousands of rocky and/or metallic bodies that are classified as minor planets. The largest asteroids are almost the size of Pluto, the smallest are little more than space pebbles.

The average spacing between the orbits of Jovian planets is

Figure 8. A montage of the nine planets represented at their correct sizes relative to Jupiter. Images courtesy of NASA.



Planet	Size (radius, km)	Orbital Period	Distance from Sun (million km)	Principal Atmospheric Gases
Mercury	2,440	88 days	58 [0.4 AU]	Helium, sodium
Venus	6,052	225 days	108 [0.7 AU]	Carbon dioxide
Earth	6,378	365 days	150 [1 AU]	Nitrogen, oxygen
Mars	3,397	687 days	228 [1.5 AU]	Carbon dioxide
Jupiter	71,492	11.9 years	778 [5.2 AU]	Hydrogen, helium
Saturn	60,268	29.5 years	1,427 [9.5 AU]	Hydrogen, helium
Uranus	25,559	84 years	2,871 [19 AU]	Hydrogen, helium
Neptune	24,746	165 years	4,497 [30 AU]	Hydrogen, helium
Pluto	1,160	248 years	5,913 [39.4 AU]	None

over 8 AU. Not only are these planets much larger than terrestrial planets, but they are also much further apart. The time it takes for a planet to complete a solar orbit increases with distance from the Sun. Mercury orbits the Sun in a little less than three months while it takes Pluto nearly two and a half centuries to finish one circuit.

Technically, Pluto doesn't fit with either the terrestrial or Jovian planets. Its modest size prompted recent calls for the demotion of the smallest planet to **minor planet** status (equivalent to asteroids). Pluto, smaller than Earth's moon, is composed of ice and rock, like the asteroids, and has an odd orbit that actually takes it closer to the Sun than Neptune for part of its course. However, the dispute came to nothing when the International Astronomical Union (IAU), the body that coordinates the naming of celestial objects, closed discussion of the matter.

Earth's physical characteristics, size, and distance from the Sun have contributed to its **unique status** as the only known inhabited planet in the universe. Earth's distance from the Sun allows **water** to exist as a liquid. In contrast, water would evaporate on Mercury and Venus and freeze on Mars if atmospheric pressures were equivalent to those on Earth. The **biosphere** of Earth has moderated the composition of the atmosphere to make it more suitable for life. Vegetation absorbed large volumes of carbon dioxide and produced oxygen. Earth's **atmospheric gases** protect the planet from all but the largest incoming space projectiles (comets, meteorites) and blocks harmful ultraviolet radiation from the Sun.

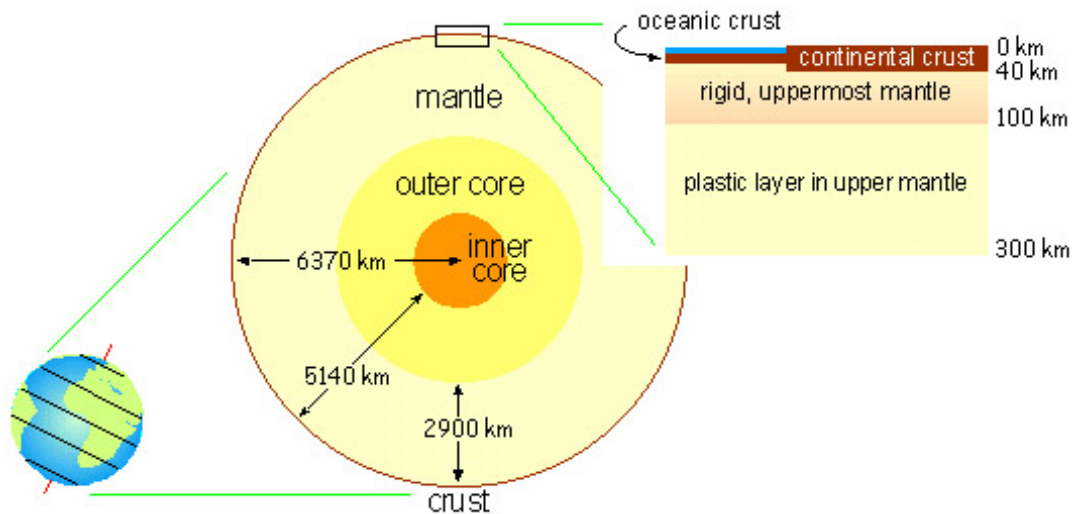


Figure 9. Earth and the other terrestrial planets can be divided into three compositional layers; crust, mantle, and core. Earth's core can be divided further into an outer liquid core and an inner solid core. The relative positions of the two mechanical layers of the crust and upper mantle (lithosphere - rigid uppermost mantle and crust; asthenosphere - plastic layer in the upper mantle) are shown in the inset diagram (not to scale).

Terrestrial Planets

The terrestrial planets are composed of rock and can be divided into **compositional layers**. The interior of Earth can be separated into three layers of different composition and thickness; the **crust**, **mantle** and **core**. These layers may be further subdivided on the basis of physical or compositional variations. For example, the composition and thickness of the crust varies below oceans and continents. Oceanic crust is typically 5 to 10 km (3-6 miles) thick whereas the average thickness of the continental crust is 40 km (25 miles) with maximum thickness of 70 km (44 miles). Continental rocks are less dense than rocks that compose the oceanic crust. (For more on how we determine the character of the Earth's interior, see Understanding Earth's Interior.)

The core is divided into two parts, a **solid inner core** and a **partially melted outer core**. Scientists realized that the outer core is liquid because some types of seismic waves will not travel through it. Earth's **magnetic field** originates from slow-moving convection currents in the outer core. The rocks of the core are largely composed of an iron and nickel mixture, metals that can be both molten and solid under the temperatures and pressures of the outer and inner core respectively. The composition of the core is similar to the composition of metallic meteorites that are thought to have formed from proto-planetary bodies elsewhere in the solar system.

Earth's magnetic field, originating from the partially molten rocks of the outer core, causes compass needles to point toward the **magnetic poles**. Although the magnetic poles are found at high latitudes they are seldom coincident with the geographical poles. The orientation of the magnetic field varies with latitude and resembles a giant dipole magnet located in the Earth's interior. The field has both declination (points toward the North Pole) and inclination (varies between horizontal and vertical). The inclination of the magnetic field is horizontal at the equator, steeper at high latitudes, and vertical at the poles (Fig. 10). The magnetic field protects us from the solar winds that destroyed much of the atmospheres of neighboring planets.

The upper part of the mantle and the crust together form two layers identified by their relative strength and physical properties. The **asthenosphere** represents a weak layer in the upper mantle composed of partially melted rock. The **lithosphere**, a relatively strong rigid layer that includes both oceanic and continental crust and the uppermost mantle overlies the asthenosphere. The different physical properties of the lithosphere and asthenosphere are the result of the interplay between pressure and temperature, both of which increase with depth. Depending upon which increases most rapidly with depth, rocks may become weaker or stronger. Increasing temperature results in weaker rocks whereas increasing pressure results in increasing rock strength.

Internal Energy and the Earth System

The processes that operate on the surface of the earth and within the planet's interior are driven by energy from different sources. **External processes** derive energy from solar radiation whereas **internal processes** are associated with heat generated from the radioactive decay of elements in Earth's interior. All terrestrial planets were much hotter when they formed and have cooled with time. Mercury and Mars, the smaller planets, lost their heat hundreds of millions of years ago but the larger planets still have hot interiors as evidenced by the volcanic activity on their surfaces. Rocks are poor conductors of heat, therefore the greater bulk of the larger planets acts as insulation, serving to maintain their internal heat.

Earth's **geothermal gradient** – the change in temperature with depth – illustrates that the planet's temperature increases with depth. The temperature gradient in the crust averages

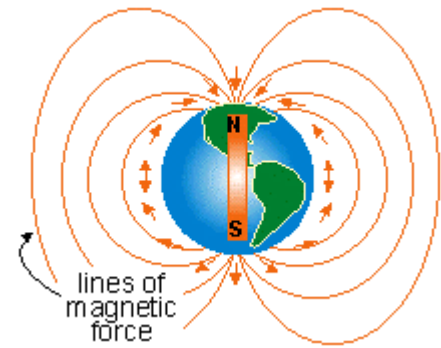
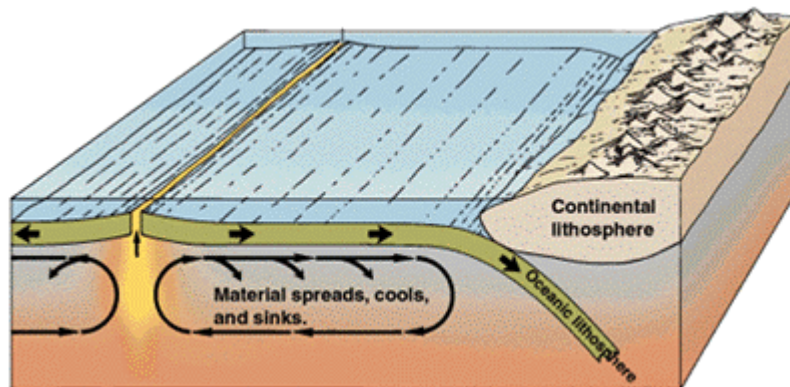


Figure 10. The inclination of the Earth's magnetic field varies with latitude. The magnetic field is inclined downward in the Northern Hemisphere and upward (away from Earth's surface) in the Southern Hemisphere.

approximately 25°C per kilometer. The geothermal gradient varies with location (higher in areas of volcanic activity) and depth and illustrates that the interior of the planet is much hotter than the exterior. Processes such as volcanism are an indication that heat is being transferred from the interior toward the surface. Heat transfer occurs by convection and conduction.

Convection is thought to occur within the uppermost layers of Earth's interior and drives the process known as plate tectonics that explains the distribution of volcanoes and earthquakes around the world. Heat flow is greatest where these convection cells come to the surface, typically at zones of continuous volcanic activity such as oceanic ridges (Fig. 11). However, heat is escaping from all parts of the surface, though at such low rates to be undetectable to only the most sensitive instruments. Such low heat flow is the result of **conduction** – the movement of heat through a solid body. For example, the handle of a metal saucepan becomes hot when left on the stove as heat is transferred from the stove through the pan to the handle by conduction. Rocks are generally poor heat conductors (or good insulators) so even though temperatures near the center of Earth are measured in thousands of degrees, heat loss at the surface is relatively modest.

Figure 11. Convection cells in the mantle are associated with oceanic ridges, regions of high heat flow on the ocean floor.



Jovian Planets

The Jovian planets are much larger than the terrestrial planets and are shrouded by dense **gases**. They may have solid cores. The **many moons** associated with these planets (Jupiter 16, Saturn 18, Uranus 15, Neptune 8) have solid cores so it is thought that the planets do also. Pressures near the centers of Jupiter and Saturn may be great enough to form layers of liquid and metallic hydrogen.

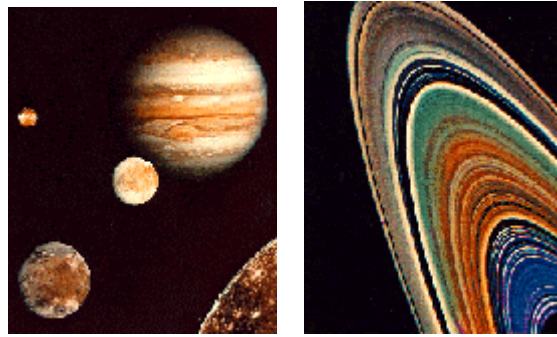


Figure 12. Left: Jupiter and moons, Io (upper left), Europa (center), Ganymede (lower left) and Callisto. Right: False color image of Saturn's rings taken by Voyager 2. Images courtesy of NASA.

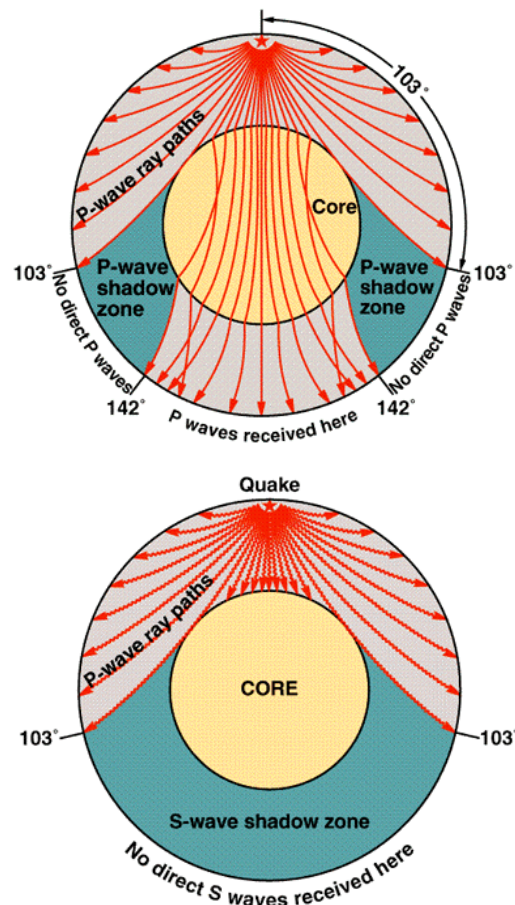
All of the Jovian planets have a **ring system**, of which Saturn's is the most obvious. Rings are composed of rocky debris or chunks of ice and are held in place by the contrasting gravitational pulls of the planets and their surrounding moons.

Understanding Earth's Interior

Even the deepest mines or drill holes do not penetrate halfway through the continental crust so how do we know what the composition of the core is at depths of over 6,000 km below the earth's surface?

Primary (P) or compression waves and Secondary (S) or shear waves are two types of seismic waves that can travel through the interior of Earth following earthquakes or large explosions. The characteristics of the wave travel paths help scientists determine compositional variations within the earth. Key characteristics are:

- P waves travel through both solids and liquids.
- S waves cannot travel through liquids
- Seismic waves travel more rapidly as the density of the material increases.
- Both types of seismic waves slow down when traveling through partially melted material.
- Both P and S waves change direction (are reflected or refracted) by boundaries between compositional layers.



P wave travel paths are deflected at boundaries between compositional layers. S waves do not pass through the liquid outer core.

Think about it . . .

Use the Venn diagram located at the end of the chapter to compare and contrast the characteristics of terrestrial and Jovian planets.

Earth & Sun

- Nuclear fusion reactions in the Sun's core generate temperatures of millions of degrees and temperature decreases outward to the Sun's surface, the photosphere.
- The solar system is defined by the limits of the Sun's magnetic field, the heliosphere.
- The solar wind, derived from the Sun's magnetic field, can disrupt satellite communication and power systems on Earth.
- The distribution of solar radiation regulates the seasons and provides the energy to drive processes on Earth's surface
- The tilt of Earth's axis is the principal reason for variations in incoming solar radiation.
- The intensity of incoming solar radiation decreases from the equator toward the poles.
- The Sun is directly over the Tropic of Cancer during summer in the Northern Hemisphere, and it lies above the Tropic of Capricorn during winter.

Number of years of
U.S. energy needs
that could be
supplied by just one
second of the Sun's
total energy output:
9,000,000

The **Sun** is the centerpoint of our solar system but is just one of billions of similar stars throughout the universe. The Sun accounts for 99.8% of the mass of the Solar System and dwarfs all its orbiting planets. Even mighty Jupiter has just a tenth of the radius of the Sun that has a diameter of 1,390,000 kilometers (870,000 miles). The Sun is a source of light and heat essential for life on Earth. This solar radiation drives the atmospheric circulation systems that provide our weather but the Sun's magnetic field yields a powerful solar wind that governs a much larger **space weather system** that extends throughout our solar system.

Characteristics of the Sun

Unlike the terrestrial planets, the Sun is composed exclusively of gases, with hydrogen and helium making up over 99.9% of

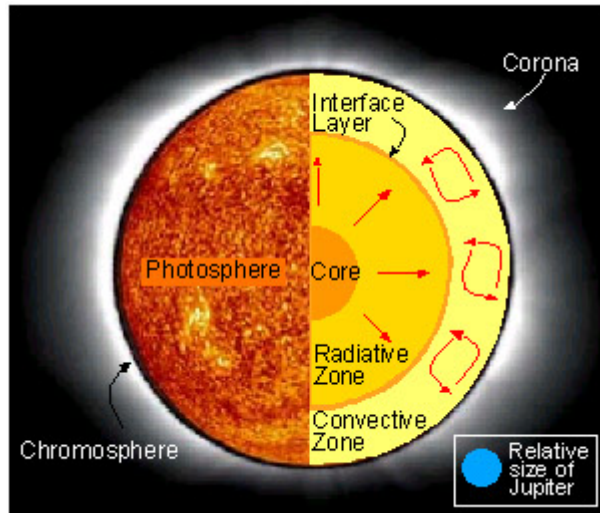


Figure 13. The interior of the Sun is composed of four principal layers. Temperatures decline outward from a toasty $15,000,000^{\circ}\text{C}$ in the core to "just" $5,430^{\circ}\text{C}$ in the photosphere. The relatively thin Interface Layer is thought to be the source of the Sun's magnetic field. We see the surface of the Sun, the photosphere. Image courtesy of NASA.

its mass. The source of the Sun's heat is the conversion of hydrogen atoms to helium by **nuclear fusion reactions** under the tremendous temperatures and pressures of the Sun's core. These reactions are steadily consuming the Sun's supply of hydrogen and reducing its mass, ensuring that our nearest star will eventually die out. In the meantime the Sun will get brighter and hotter resulting in higher temperatures on Earth, the loss of the almost all water, and the extinction of life well before the light fades. Thankfully, this grim scenario is still billions of years in the future.

Heat is transferred from the core to the outermost layers of the Sun by a combination of radiation and convection (Fig. 13). Radiation transfers heat from an object to its immediate neighbor. Convection occurs when warm and cold materials cycle through a body redistributing heat until the mixture is at equilibrium. For example, when a metal saucepan of water is heated, the warmest water at the bottom of the pan expands and rises and the cooler water at the top sinks forming a rotating convection cell. Heat is distributed throughout the pot as the process continues. In contrast, the heat from the stove passes through the base of the pan and upward through the metal into the handle of the pan by radiation. Radiation transfers heat from the core outward through the **radiative zone**. Convection cells in the **convective zone** redistribute heat from the Sun's interior toward its outer surface.

The **interface layer** marks the boundary between zones of convection and radiation in the Sun's interior and is thought to be the source of the **heliosphere**, the Sun's magnetic field. The magnetosphere extends beyond the orbit of Pluto and defines

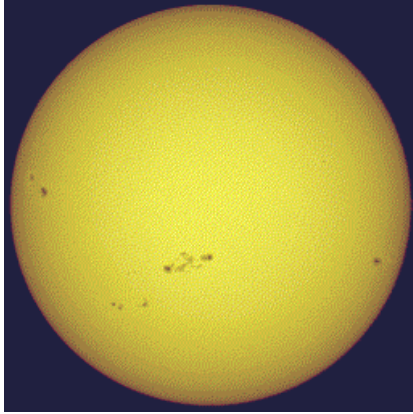
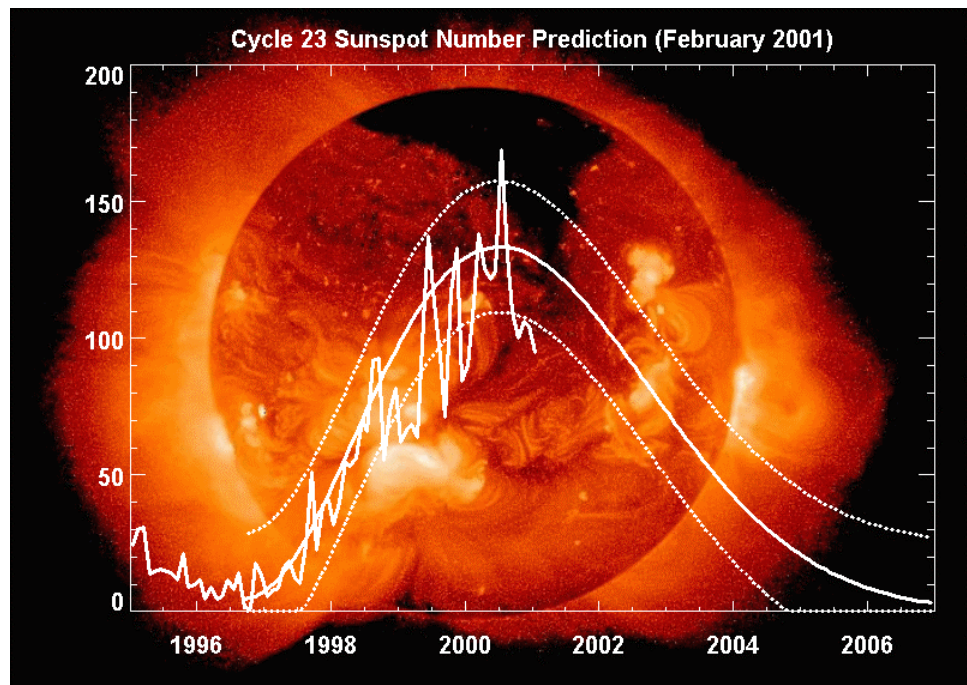


Figure 14. Dark blotches on the photosphere are sun spots. Image courtesy of NASA.

the boundary of the solar system. The Sun rotates about a near-vertical axis about once a month. However, this big ball of gas experiences **differential rotation**, that is, its equator rotates more rapidly than its polar regions. Equatorial regions of the Sun make a complete rotation every 25 days while the poles may take 36 days. Differential rotation causes twisting of the Sun's outer layers, causing disruptions in the magnetic field that generate sun spots and flares, visible features in the **photosphere** and chromosphere. The photosphere is the thin outermost layer of the Sun, the surface of the Sun we see through telescopes.

Sun spots have been recognized on the surface of the Sun for several centuries and their apparent movement across the Sun's face can be used to measure the periodicity of the Sun's rotation. Sun spots (Fig. 14) represent cooler areas of the photosphere ($3,530^{\circ}\text{C}$) where intense lines of magnetic force emanate outward. Individual sun spots may be as large as 50,000 km (31,000 miles) in diameter, the approximate size of Neptune. The number of sun spots varies over an eleven year cycle (Fig. 15). We passed through a peak, known as a **solar maximum**, in the sun spot cycle in the early months of 2001 and are expected to reach the minimum of the cycle in late 2006. There is an intriguing correlation between the period of sun spot inactivity between 1645-1715 known as the Maunder

Figure 15. Graph of sun spot numbers for the current sun spot cycle. Image courtesy of NASA.



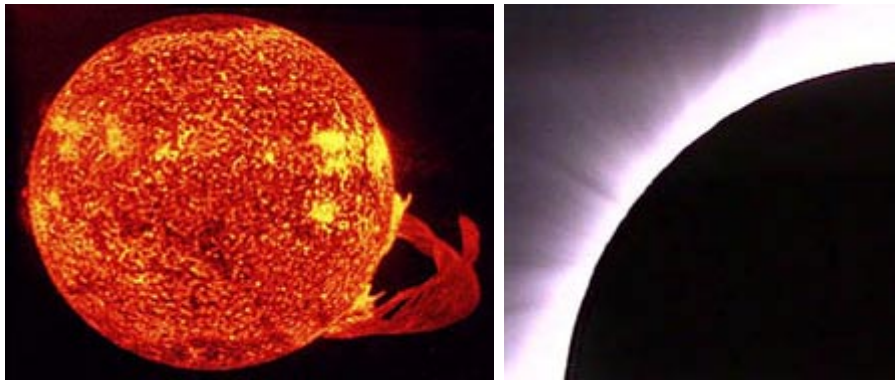


Figure 16. Solar eruptions take several forms including prominences (left) that project far above the Sun's surface. The bright light of the solar corona (right) is only visible during solar eclipses. Images courtesy of NASA.

Minimum and the Little Ice Age, an interval of colder-than-average years in the Northern Hemisphere.

Flares, intense pulses of X rays, ultraviolet radiation, are often associated with sun spots. Flares and other solar eruptions extend into the **chromosphere**, an irregular layer above the photosphere (Fig. 16). The **solar corona** extends for millions of kilometers beyond the chromosphere but is only visible during total eclipses.

Space weather is influenced by flares, sun spots, and coronal emissions but these activities are overprinted on the **solar wind**, a constant stream of charged particles emitted by the Sun's corona. These particles travel at average speeds of 450 km/sec (1 million miles per hour) and can cause **disruptions in Earth's magnetic field** and spectacular effects such as the aurora borealis in the upper atmosphere.

Earth's magnetic field deflects the solar wind around our planet, protecting our atmosphere (Fig. 17). Were it not for the presence of the magnetic field our atmosphere would have been steadily stripped away, just like the envelope of gases that

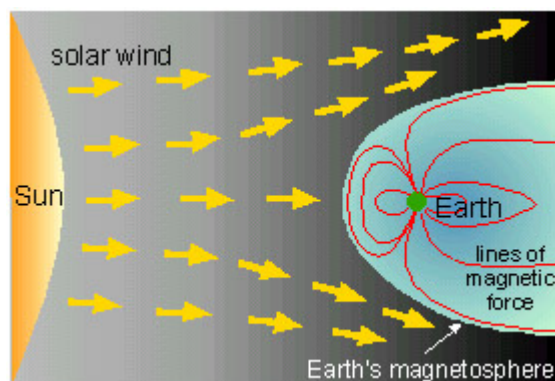


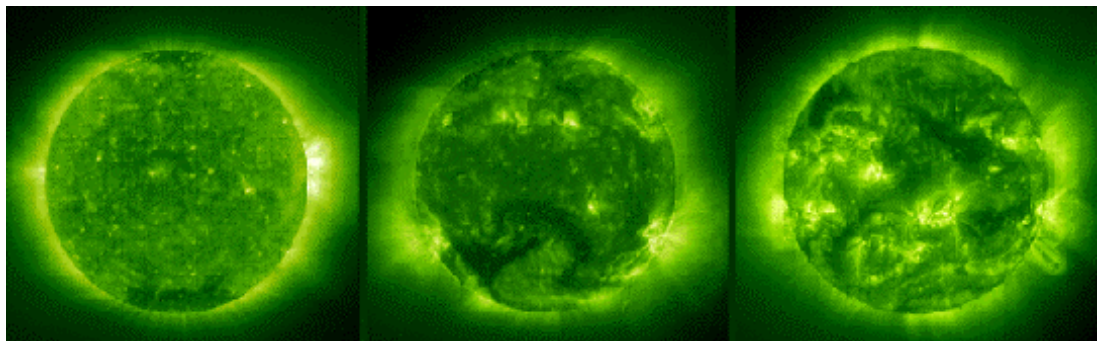
Figure 17. Earth's magnetic field deflects the solar wind. The magnetosphere is compressed on the side of the planet that faces the Sun.

once surrounded Mars. The red planet lost its protective magnetic field as the smaller planet cooled down more rapidly than Earth, losing its hot liquid core. **Mars** retains just isolated remnants of its atmosphere where pockets of relict magnetism remain.

Although our planet's magnetic field protects us from the erosion of our atmosphere, we are still subject to the harmful effects of occasional solar eruptions that hurl more intense pulses of X rays, ultraviolet radiation, and charged particles toward Earth. Living on the planet's surface we are at little risk of direct harm from these emissions but they pose a threat to astronauts and spacecraft and have the potential to cause disruption of our communication and power supply systems. We depend on over six hundred operational satellites to provide information for a host of needs on Earth, including communications, navigation, and weather forecasting. Many of these **satellites** would be debilitated by streams of solar radiation.

Figure 18. Three views of the Sun taken by the SOHO satellite showing increasing solar activity (more sun spots, solar flares, prominences, and coronal mass ejections) approaching a solar maximum, a peak in the sun spot cycle. Dates of images are 1997 (left), 1998 (center), and 1999 (right). Image courtesy of NASA.

Intense streams of charged particles can disrupt Earth's magnetic field, generating electrical currents that result in power surges leading to blackout conditions as electrical systems shut down. Over six million people in eastern Canada and the northeastern U.S. lost power for nine hours in March 1989 because of a powerful solar storm that coincided with a solar maximum. The economic costs of power outages are measured in hundreds of millions to billions of dollars. Satellites such as SOHO (Solar and Heliospheric Observatory) monitor activity in the Sun's photosphere and chromosphere and can provide notice of potentially damaging bursts of solar energy heading for Earth (Fig. 18). Such warnings will be vital to future space exploration that will expose astronauts to deadly radiation emissions. Construction of the international



space station will imperil the lives of space-walking astronauts unless solar storms can be accurately forecast and sufficient warning given.

The Earth-Sun System

Weather and climate are the result of a complex series of interactions between all elements of the earth system (hydrosphere, atmosphere, biosphere, solid earth) but are largely controlled by the interaction between the Earth and Sun. The distribution of **solar radiation** on Earth's surface regulates the order of the seasons and divides day and night. The Northern Hemisphere receives more solar radiation in summer and less in winter. Surely, there are few more basic scientific questions than: Why is it colder in winter than in summer? (What is your answer?) Yet even graduating seniors at a prestigious eastern university were unable to answer the question correctly (almost all got it wrong). The most common explanation given was that Earth was closer to the Sun in summer and further away in winter - unfortunately, the exact opposite is true (Fig. 19). Earth's orbit is a little uneven and the planet comes closest to the Sun during winter in the Northern Hemisphere (January 3) and is farthest away during Summer (July 4).

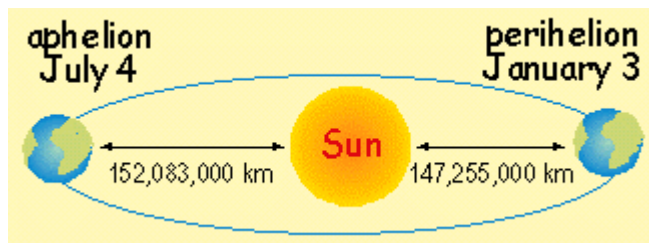


Figure 19. Earth is farthest from the Sun at its aphelion and closest during its perihelion.

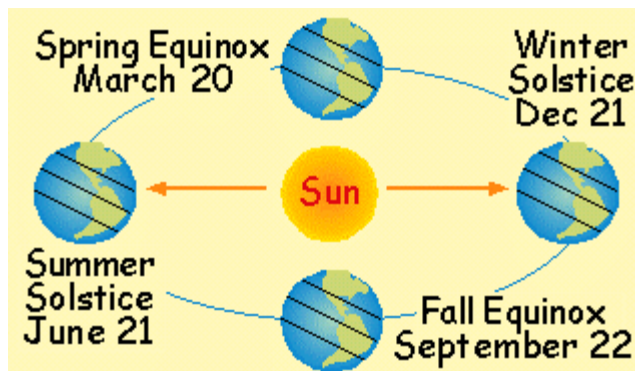
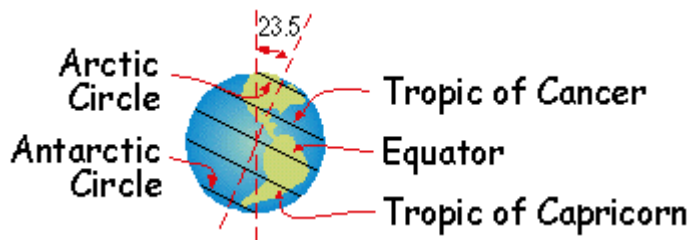


Figure 20. The Sun is overhead at the Tropic of Cancer on June 21 and at the Tropic of Capricorn on December 21. It is overhead at the equator during the spring and fall equinoxes.

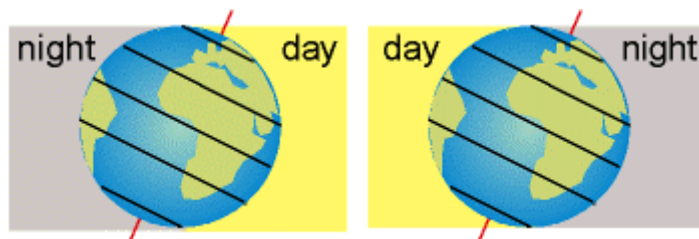
The principal reason for the seasonal differences in climate around the globe is the **tilt of Earth's axis** (Fig. 20). Earth rotates around an axis that is tilted 23.5 degrees to vertical. The Tropics of Cancer and Capricorn are located 23.5 degrees north and south of the equator, respectively (Fig. 21). **Insolation**, the amount of solar radiation received by Earth, is greatest when the Sun is directly above a location on Earth and decreases as the angle of the Sun's rays becomes more oblique. The axial tilt places the Sun directly overhead at the Tropic of Cancer in the Northern Hemisphere during the **summer solstice** (June 21). Likewise, the Sun's rays strike the Northern Hemisphere more obliquely when the Sun lies over the Tropic of Cancer in the Southern Hemisphere during the **winter solstice** (December 21).

Figure 21. Relative positions of the Equator and tropics. The Arctic and Antarctic Circles are located 66.5 degrees north and south of the equator (or 23.5 degrees south and north of the North and South Poles, respectively).



Day and night would each last exactly 12 hours everywhere on the globe if Earth's axis were vertical. In contrast, the hours of daylight change at each point in the Northern Hemisphere from a maximum during the summer solstice to a minimum on December 21 when the Sun is directly overhead at the Tropic of Capricorn. Day and night are split equally during the equinoxes. The length of each day increases traveling northward during summer in the Northern Hemisphere and decreases southward in the Southern Hemisphere. Perpetual daylight (24 hours) occurs at the North Pole, while the South Pole is in darkness. This pattern is reversed during the winter

Figure 22. The tilt of Earth's axis results in 24-hour daylight at the North Pole and almost complete daylight north of the Arctic Circle during summer in the Northern Hemisphere (left) and perpetual darkness during winter (right). The situation is reversed south of the Antarctic Circle.



solstice when the South Pole is illuminated for 24 hours and the North Pole is in darkness (Fig. 22).

Think about it . . .

How would climate differ if Earth's axis was vertical instead of tilted?

External Energy and the Earth System

A fraction of the Sun's energy reaches the earth as solar **radiation**, the process by which heat passes through a gas, liquid, or vacuum. Most solar radiation reaching Earth is absorbed by the land or oceans. Air masses are warmed or cooled by the land or ocean below. Warm tropical air rises over the equatorial oceans. As the air rises it gradually cools and releases moisture as rain. Cooler air eventually sinks, returning to the surface to repeat the cyclical journey that represents **convection**, the movement within materials driven by different temperature conditions.

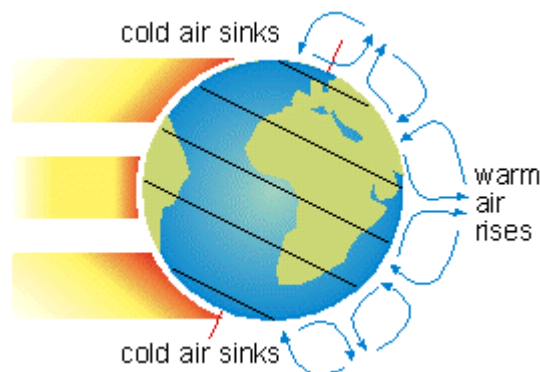


Figure 23. Atmospheric convection cells generated by contrasts in solar radiation on a rotating Earth.

Near Earth Objects

- NEOs (near Earth objects) are asteroids or comets with an orbit that brings them relatively close to Earth.
- Asteroids originate in the asteroid belt between Mars and Jupiter; comets are formed beyond the limits of our solar system.
- There are over a thousand NEOs with a diameter of 1 km or more and millions of smaller objects.

- Asteroids that reach Earth's surface are termed meteorites and are composed of materials similar to those of our planet's core, mantle, and crust.

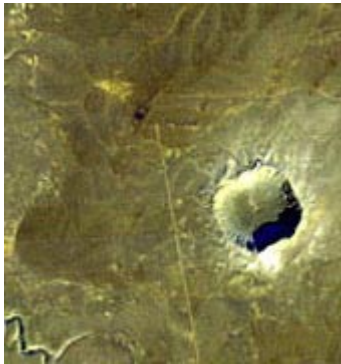
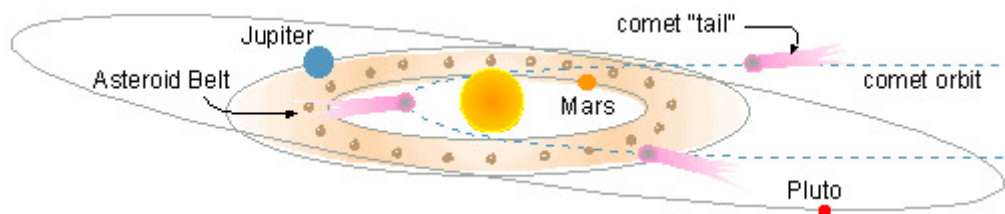


Figure 24. The 1.2 km-wide Meteor (Barringer) Crater, near Winslow, Arizona was formed 50,000 years ago by the impact of a meteorite with a diameter of approximately 50 meters.

The term near Earth object (NEO) is used to refer to objects such as asteroids or comets that approach Earth. **Asteroids** originate in the **asteroid belt**, a relatively dense jumble of cosmic debris that lies in orbit between Mars and Jupiter. The gravitational attraction of nearby Jupiter jostles asteroids from their consistent orbit causing them to crash into one another. These collisions can send small asteroids or crash debris looping through space toward the inner planets. These materials follow eccentric orbits and can plunge into any of the terrestrial planets, leaving impact scars that can still be observed today (Fig. 24). An asteroid on a course to collide with Earth is termed a **meteoroid**. The actual object that strikes Earth's surface is termed a **meteorite**. Therefore, meteorites and asteroids are essentially the same thing, just in different locations. Asteroids range in size from little more than space dust to nearly 1,000 km in diameter.

Figure 25. Meteorites that strike Earth's surface originate in the asteroid belt between Mars and Jupiter. Comets originate beyond our solar system. Comet "tails" are oriented away from the Sun and indicate the direction of the solar wind. Pluto's orbital path is inclined relative to the orbits of the other planets. Diagram not to scale.

Comets originate beyond the margins of our solar system and approach the Sun on wide elliptical orbits (Fig. 25). Like the distant Jovian planets located far from the Sun's heat, much of a comet's mass is composed of ice, probably surrounding a rocky core. The ice evaporates as the comet approaches the interior of the solar system, forming a trailing tail that points away from the Sun in the direction of the solar wind. Although comets do not collide with Earth as frequently as asteroids the consequences of an impact would be just as catastrophic. A mysterious 1908 explosion in **Tunguska**, Siberia, has been attributed to the air blast of a comet that disintegrated in the atmosphere a few kilometers above the land surface. The blast left no crater but flattened forests over an area of 2100 square kilometers (840 square miles) and would be sufficient to lay waste to the largest urban areas on Earth.



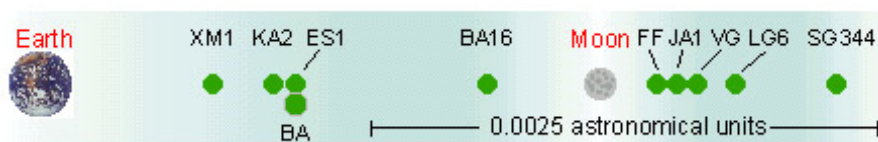
A string of up to 20 separate parts of a comet known as Shoemaker-Levy smashed into Jupiter over the span of a week in 1994. This was the first time scientists were able to observe a collision between two bodies in our solar system.

An estimated 100 million kilograms of meteorites strike Earth's atmosphere each year with the bulk of this material in the form of small particles. Frictional heating of these objects as they fall through the atmosphere ensures that most are vaporized well before they can reach Earth's surface. Fortunately, the largest asteroids are not heading for Earth but the impact of an object of less than 100 meters diameter would be sufficient to destroy a large city. A 50 meter (165 feet)-wide meteorite gouged out **Meteor Crater**, a deep hole over a kilometer (0.6 miles) wide in the Arizona desert. (For more on impact features see Impact Hazards).

Astronomers have estimated that there are approximately a thousand asteroids, with diameters of over 1,000 meters and estimate that there are another million that are 50 meters in diameter or larger. Scientists are currently focusing their detection efforts on the largest NEO's that could cause catastrophic global or continental-scale consequences should they impact Earth (Fig. 26). There is no program to locate small asteroids of less than 1 km diameter because they are too small to detect easily and there are too many to find with current resources. (For more on detection of NEOs see Beware Flying Rocks.)

Meteorites found on Earth's surface are composed of rocks or metals or some combination of both. **Stony meteorites**, composed of rocks similar to those found in Earth's crust or mantle, account for over 90% of known meteorites. Six percent of meteorites are made up of a mix of iron and nickel and are known as **irons**. These metals are thought to form Earth's core. The contrasting composition of meteorites is interpreted to reflect the fact that asteroids are composed of the same materials as the terrestrial planets. A small number of meteorites are composed of rocks similar to those found on the Moon or Mars. These meteorites are thought to have been

Figure 26. Proximity of NEOs to Earth and Moon. At least five NEOs have approached Earth more closely than the distance to the Moon in the last decade. The closest approach was by meteorite XM1 that came within 112,000 km (70,000 miles) of Earth in December 1994. All of the NEOs shown are several kilometers in diameter. One astronomical unit is the distance from Earth to the Sun.



knocked into orbit by an earlier collision of asteroids with the lunar or martian surfaces.



Figure 27. NASA landed a small spacecraft on the Eros meteorite. Image courtesy of NASA.

The five-year **Near Earth Asteroid Rendezvous** mission (NEAR) placed a spacecraft in close orbit with the asteroid known as 433 **Eros** (Fig. 27). The goal of the mission was to learn more about the geology and physical properties of NEOs. Future efforts to destroy or deflect incoming asteroids will require an understanding of the composition and rotation sequence. Some bodies may have larger proportions of metals, others may be little more than rubble piles. Understanding the makeup of asteroids will help scientists better determine how to protect against their collision with Earth. Eros is a large peanut-shaped asteroid, 33 km long (21 miles) and 13 km (8 miles) around. Its surface is pockmarked with craters, some up to 6 km (4 miles) across. Eros is made up of solid rock with density similar to Earth's crust in contrast with the asteroid Mathilde, which was visited earlier in the mission and discovered to be little more than a pile of debris. The NEAR mission ended dramatically with the spacecraft landing on the surface of Eros in February 2001. Such maneuvers may be necessary in the future if scientists need to place explosives in key locations on an asteroid on a collision path with Earth.

Think about it . . .

Complete the second Venn diagram at the end of the chapter to compare and contrast the characteristics of planets in our solar system and asteroids.

Impact Hazards

- Craters formed by the impact of a comet or asteroid with Earth have either a simple bowl shape (smaller craters) or a more complex structure featuring a central peak.
- There are over 150 recognized impact craters worldwide
- Impact events generate a series of associated features, including craters, ejecta, shock metamorphism, breccia, and melt rocks.
- The impact of a large comet or meteorite with Earth could devastate the global environment by generating air blasts, earthquakes, wildfires, and tsunamis, and by blocking sunlight for months and altering the composition of the atmosphere.

Impact craters are common on all the rocky terrestrial planets and their moons (Fig. 28). The majority of the craters formed during a period of intense bombardment soon after the

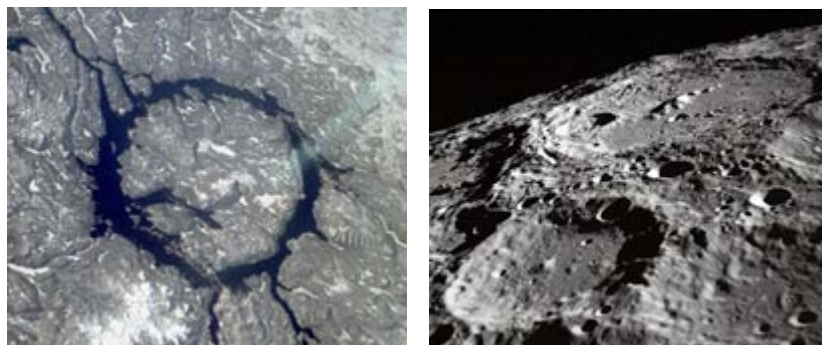


Figure 28. Left: Manicouagan impact crater, Canada, a 70 km wide circular lake surrounds the crater site formed by an impact 200 million years ago. Much of the original 100 km-wide crater has been obliterated by erosion but melt rocks of the crater floor remain. This is one of the largest terrestrial impact craters. Right: craters are more common on the Moon. Images courtesy of NASA.

formation of the solar system. All of these early craters date from before 3.9 billion years ago. More recent impacts on Earth are preserved in relatively young rocks as older impact craters are either worn away by erosion and weathering or were covered up by later rock layers. Craters are preserved in their original state on the Moon where the lack of atmosphere ensures that they won't be worn away by the action of wind and water.

Impact craters on Earth come in two basic forms (Fig. 29). Smaller **simple craters** such as Meteor Crater, Arizona, have a diameter of a few kilometers and exhibit a simple **bowl-shaped** morphology (Fig. 30). Larger **complex craters** with diameters of more than 4 km (2.5 miles) are characterized by **central peaks** and ring-like structures along their margins where the crater rim collapsed inward (Fig. 31). Crater size is largely a consequence of the size and velocity of the impacting meteorite or comet and the character of the impact site.

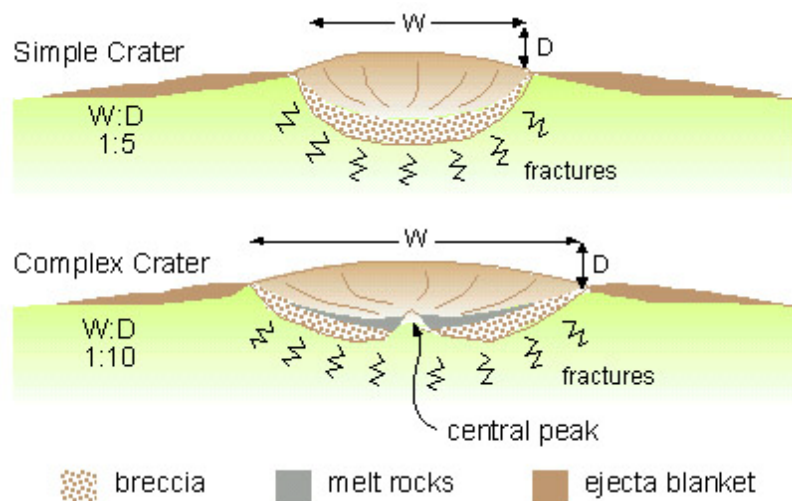
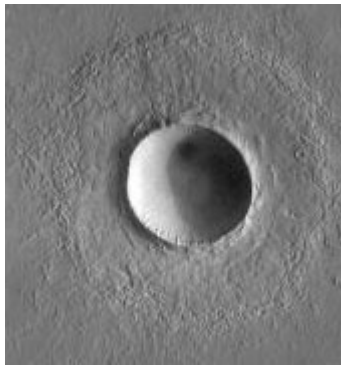


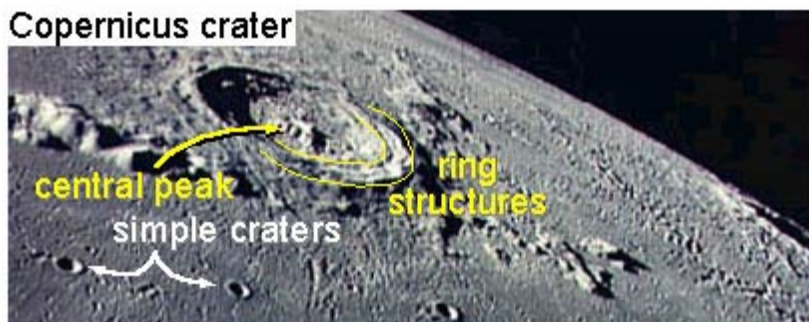
Figure 29. Bowl-shaped simple craters exhibit fewer features and a smaller width-to-depth ratio than larger complex craters.

Figure 30. A simple crater on Mars approximately 2 km across. Note ejecta blanket preserved around the crater. Images courtesy of NASA.



Craters often contain smashed rocks known as **breccia** and may be surrounded by a blanket of **ejecta**, displaced particles thrown outward by force of the impact. Heat from the impact can cause melting of rocks on the crater floor. The impacting body is typically pulverized by the force of the collision although some small fragments may occasionally be preserved. The atomic structures of minerals in the rocks of the impact site will be altered by the extreme force of the collision to form a suite of features that are unique to impact events. These changes, evident only under the microscope, are collectively termed **shock metamorphism** and are an unmistakable signal of impact events.

Figure 31. Copernicus crater a complex crater on the Moon exhibiting a central peak and ring structures. Note simpler bowl-shaped small craters. Image courtesy of NASA.



Scientists have identified approximately **150 impact sites** on the continents (Fig. 32). Impacts that occurred in the oceans may not have been large enough to form craters on the ocean floor or the locations may have been destroyed or obscured by geological processes. The largest craters are formed by meteorites approximately 10 km (6 miles) in width or larger. Such events are relatively infrequent and are separated by hundreds of millions of years. The most recent such event occurred 66 million years ago, forming the **Chicxulub** impact structure on the Yucatan Peninsula, Mexico, and is thought to have caused a worldwide extinction that wiped out 70% of



Figure 32. Locations of impact events discussed in text. Numbers refer to identified craters per continent. Over 150 craters have been recognized. It is likely that exploration of less-accessible regions of Earth will yield many more examples.

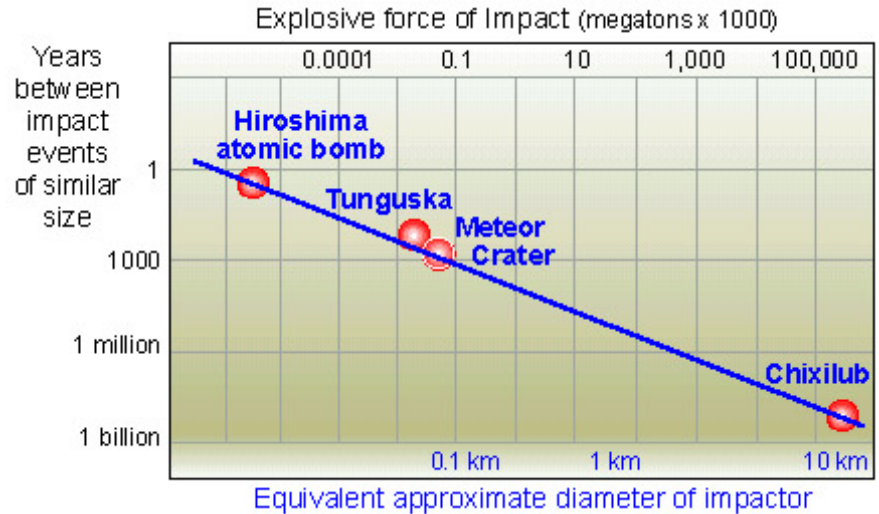
species. These large-scale impacts leave a clear imprint in the geological record that can be readily documented. A meteorite of 1 km (0.6 miles) in diameter is sufficiently large to devastate most nations and objects just 50 to 100 meters (160-330 feet) across could level whole cities. The explosive force of the relatively small meteorite that carved out **Meteor Crater**, Arizona, was several thousand times greater than the atomic bomb dropped on Hiroshima at the close of World War II.

Environmental Consequences of a Large Impact Event

It could be a day like any other. The entry of a large asteroid or meteorite into Earth's atmosphere may occur with no warning or it could be predicted decades in advance and watched anxiously by billions of people around the world. It would be accompanied by an **atmospheric shock wave** and the frictional heating of the speeding object would cause it to glow as it plunged through the atmosphere. For many, this might be their first warning of their fate. The **fireball** would take just 15 to 30 seconds before making impact, too little time to take any actions that would permit survival for those close to the impact site. The collision would send out a powerful **air blast** that would flatten everything for hundreds of kilometers in every direction. Anything that survived the air blast would be rocked by a **massive earthquake** hundreds or thousands of times greater than the largest ever recorded (Fig. 33).

The impact would gouge out a **deep crater** about 10 to 20 times larger than the colliding meteorite/asteroid. The Chicxulub Crater in Mexico is approximately 200 km (125 miles) diameter and was formed by a meteorite up to 10 km (6 miles) across. The air blast from the impact event felled forests 2,000 km away in the interior of North America. Almost every living thing in southern North America or northern South America would have been killed by the collision. The impact would pulverize rocks, ejecting a massive plume of **dust and**

Figure 33. Frequency of impact events of contrasting sizes. The largest impacts occur on time intervals measured in hundreds of millions of years. Impacts large enough to destroy a large city or have substantial regional consequences occur every 100 to 1,000 years.



melted rock fragments upward into the atmosphere. There would be sufficient dust in the atmosphere, potentially for several months, to **block sunlight**, leading to lower temperatures and a short-term cooling trend. Scientists have estimated that Earth was in darkness for up to six months following the Chicxulub impact which may have been sufficient to prevent photosynthesis for the next year. Vegetation would not survive without the ability to enter a dormant phase until conditions improved sufficiently to once again allow photosynthesis.

Pieces of molten rock blasted out of the crater would fall back to Earth to generate colossal **wildfires** that would add smoke to the rapidly darkening skies. Tiny globules of molten material would form glassy spheres known as **spherules** that are indicative impact events. Some of these particles would travel fast enough to leave the atmosphere and orbit Earth before falling back to the surface. An impact event in the open ocean would generate a **giant tsunami** that would drown coastal regions and travel far inland. Waves with heights measured in thousands of meters (0.6-2 miles) would be possible from a Chicxulub-sized event in the deep ocean. A 10 km-wide impactor would be over twice the average depth of the ocean floor. The tsunami associated with Chicxulub was muted as only a portion of the impact was located in the shallow waters of the Gulf of Mexico along the margin of the Yucatan Peninsula. The impact generated tsunamis up to 300 meters (1,000 feet) high that pushed into the present Gulf Coast states and created sufficient backwash to carry forest debris up to 500 meters (0.8 miles) offshore.

Finally, **atmospheric chemistry** would be changed as gases derived from ocean waters or pulverized rocks would be added to the atmosphere. Gases such as sulfur dioxide, carbon dioxide, and water vapor could have residence times in the atmosphere measured in years to decades and could remain after the dust settles and wildfires burn themselves out. Injections of sufficient sulfur dioxide would result in global acid rain conditions. The potential consequence of these additional greenhouse gases is to trap more solar radiation and generate a **warming trend** in the decades following the impact.

Think about it . . .

Draw a diagram or make a concept map that summarizes the consequences of the impact of a large asteroid with Earth.

Beware Flying Rocks

- The collision of an asteroid or comet with Earth is the only natural hazard we have the potential to prevent.
- Prevention requires early detection of incoming NEOs by space surveys such as Spaceguard.
- The potential risk of collision can be calibrated using the Torino scale.

Even when scientists know the location, speed and trajectory of Earth-orbiting objects it is not an easy task to predict exactly where they will enter the atmosphere and crash to Earth. The 140-ton **Mir** space station, the largest constructed object to come back to Earth, crashed in the south Pacific Ocean in March 2001. While most of the components burned up in the atmosphere, approximately 50 tons of debris splashed down in a zone covering thousands of square kilometers between New Zealand and Chile. There was sufficient concern about the re-entry that the Russia space agency bought a \$200 million insurance policy to guard against stray fragments causing harm. Undaunted by such uncertainty, a group of observers paid over \$6,000 each to charter planes to fly above the splash-down zone in hopes of catching a view of blazing space debris zipping by their window seat. Proving that money and good sense often don't go together, these spectators were fortunate

NASA's
annual
budget for
detection of
NEOs:
\$3 million



Figure 34. Close examination of asteroids like Eros will provide scientists with information on how best to deflect or destroy incoming NEOs. Image courtesy of NASA.

in that their unique form of Russian roulette did not end with a flaming space toilet knocking them into the ocean.

Impact events represent the only significant **natural hazard that we have the potential to prevent**. We do not have the technology to stop volcanic eruptions or earthquakes but we are close to having the technical ability to prevent flying space rocks from smashing into our planet. With just a few days warning we could readily anticipate the approximate impact site for an Earth-bound asteroid or comet. Given its size and speed (Fig. 34), scientists could predict the potential consequences of the impact and make efforts to evacuate the region and prepare for the collision. However, if we have warning times measured in years or decades it is possible that the object could be **deflected** away from Earth or **destroyed** before it enters our atmosphere. Efforts to prevent a collision would center around detonating an explosion near the NEO. At great distances, even a small nudge would be sufficient to avoid a collision but closer objects might require the explosive force of a nuclear warhead to push it off track or break it into smaller, less threatening pieces. The key step is finding the object and correctly determining its path toward Earth.

There is just one caveat. NEO hunters are only focusing on big rocks of **over 1 km in diameter** that would have the potential to create a continental- or global-scale catastrophe. There is no effort being made to detect asteroids and comets capable of generating impacts similar to Tunguska or Meteor Crater (see Impact Hazards section). Essentially, we are accepting that major cities like London or Paris could be obliterated without warning but are doing our best to ensure that areas the size of Europe would not be decimated. The reasons behind such a scale-dependent response are tied to the difficulty in finding NEOs, the available resources, current funding for NEO detection programs, and recognized levels of risk.

Most NEOs are asteroids, small, dark, distant, mobile objects that reflect little sunlight and are therefore difficult to see. Less than one hundred people around the world are working at the few facilities with the telescopes and automated cameras necessary to detect NEOs. These programs photograph the night sky at specific time intervals and seek to find objects that change location relative to the fixed background of stars. The paths of newly discovered asteroids are then calculated and plotted. If the path approaches Earth based on the relatively small data set, scientists will use archival data to expand the

record and predict a more accurate orbit for the asteroid. They will then calculate the distance of the object from Earth and the specific date of its approach.

Scientists rank natural hazards using a variety of scales intended to reflect the potential dangers of a hazard. For example, the Saffir-Simpson scale ranks hurricanes by wind speed and the Richter scale measures shaking associated with earthquakes. Astronomers have developed the **Torino scale** to assess the potential risk from impact events. A Torino scale value of 0 to 10 is assigned to a NEO reflecting its potential to strike Earth and the consequences of that collision. A value of 0 (zero) represents an NEO that will either miss Earth or burn up in the atmosphere. Occasionally astronomers identify approaching asteroids that on initial examination have a slim chance of striking Earth (1 or 2 on the Torino scale). However, on closer examination it has been determined that these objects will miss us by a sizable distance and the chance of collision is downgraded to 0.

Torino Scale

Events with no consequences

0 Objects will miss Earth or burn up in the atmosphere.

Events meriting careful monitoring

1 Little chance of collision, should be monitored to confirm object will miss.

Events meriting concern

2 Close approach, collision unlikely.

3 Close approach, slight chance of collision by small body.

4 Close approach, slight chance of collision by larger body.

Threatening Events

5 Close encounter, significant threat of collision and regional devastation.

6 Close encounter, significant threat of collision and global devastation.

7 Close encounter, extremely significant threat of collision and regional devastation.

Certain Collisions

8 Collision causing localized destruction.

9 Collision causing regional destruction.

10 Collision causing global destruction.

- Lifetime risk of death in U.S
- . . . from fire:
1 in 800
 - . . . from airplane accident:
1 in 20,000
 - . . . from comet or asteroid impact:
1 in 20,000
 - . . . from tornado:
1 in 60,000.

Scientists estimate that there are approximately **1,000 NEOs** of 1 km in diameter or greater. We know the orbits of about half of these objects and present search programs are looking for the remainder. None of the recognized objects are headed for an impact with Earth but an unknown asteroid could smash into the planet tomorrow and we would be none the wiser. NASA (National Aeronautics and Space Administration) began the aptly named **Spaceguard program** to detect NEOs in 1998 with the goal of finding 90% of NEOs with a diameter of 1 km or greater within a decade. Even if these detection programs are successful, that still leaves an estimated million objects with diameters of less than 1 km that have not been identified. These smaller objects are large enough to reach the surface of Earth and wipe out a city and devastate most nations. Asteroids with diameters of approximately 2 to 3 km (1.2-1.8 miles) strike Earth on average every million years but 50 meter (160 feet)-wide objects crash to Earth once a century. Imagine an event similar to those at Tunguska or Meteor Crater taking place in your lifetime.

Scientists are looking for the largest NEOs first, not only because they will be the easiest to find but also because the risk they pose is the greatest. They may only strike the planet on time intervals measured in millions to hundreds of millions of years but their consequences would be so catastrophic that they could end human life. Smaller impactors, although more likely to hit the planet, would have a more localized significance, causing severe regional devastation but having little consequence for the vast majority of life on Earth.

Think about it . . .

It is 20 years in the future. Scientists have found four asteroids that will collide with Earth. You are given the assignment to create an evaluation rubric to rank the relative dangers from the potential collisions. The impact that scores the highest will be the first to be targeted for destruction. Go to the end of the chapter to complete the exercise.

Summary

1. What are the four components of the Earth system?

Hydrosphere, atmosphere, biosphere, rocks (lithosphere).

2. Name the three compositional layers of the earth's interior.

The three layers of Earth's interior are the crust, mantle, and core. The core can be subdivided into a solid inner core and a liquid outer core. The crust is separated into thin oceanic crust and thicker continental crust.

3. How have scientists determined the characteristics of Earth's interior?

Seismic waves change direction when they cross a boundary between compositional layers in the Earth's interior. The velocity of seismic waves increases with increasing density (depth) and decreases with the presence of partially molten material. Seismic waves are generated by earthquakes or human actions. Geophysicists ascertain the composition of Earth's interior by determining the route followed by seismic waves and the length of time to reach a recording station.

4. Name the two mechanical layers identified in the outer few hundred kilometers of Earth.

Lithosphere and asthenosphere.

5. How does the composition of the lithosphere and asthenosphere differ?

The rigid lithosphere is made up of the crust and uppermost mantle. The base of the lithosphere varies in depth but lies approximately 100 km below Earth's surface. Rocks in the uppermost mantle that lie within the asthenosphere are partially molten.

6. What are the sources of energy for external and internal earth processes?

External processes are driven by energy from the Sun; internal processes are driven by heat energy from radioactive decay of elements within Earth's interior.

7. Name the three processes by which heat energy is transferred to Earth or within Earth.

Radiation transfers heat from the sun to Earth through the vacuum of space and the gases of Earth's atmosphere. Heat is transferred from Earth's interior to the surface by conduction

(the movement of heat through a solid body) and convection (upwelling of magma).

8. What is the difference between the terrestrial and Jovian planets?

The earth is one of the terrestrial planets (with Mercury, Mars, and Venus) that are solid and composed of compositional layers. Saturn, Jupiter, Neptune and Uranus are included in the larger Jovian planets, dominated by gases.

9. List the order of the planets with increasing distance from the sun.

In order, with increasing distance from the sun the planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto.

10. What are the characteristics of the terrestrial planets?

All were bombarded with meteorites during their early history; they were much hotter when they formed and have cooled with time; large planets (Earth, Venus) have hot interiors (both have volcanism) but the smaller Mars and Mercury cooled down billions of years ago.

11. What are the characteristics of the Jovian planets?

The interiors of Jovian planets are hidden behind an impenetrable blanket of gases; Jovian planets have many more moons than terrestrial planets (Jupiter 16, Saturn 18, Uranus 15, Neptune 8); all Jovian planets have ring systems.

12. What is an NEO?

NEO is an abbreviation for near Earth object, a term used to refer to objects such as asteroids or comets that approach Earth. Asteroids originate in the asteroid belt between Mars and Jupiter. An asteroid that strikes Earth's surface is termed a meteorite. Comets originate beyond the margins of our solar system and approach the Sun on wide elliptical orbits. Much of a comet's mass is composed of ice, surrounding a rocky core.

13. Has an NEO actually hit Earth during recorded history?

Yes. Meteorites strike the planet all the time. Small meteorites weighing a few kilograms (5-10 pounds) are found frequently but their actual impact with the Earth is rarely observed. Such small objects do little damage and apart from striking cars or homes rarely threaten life or property. In contrast, NEOs that are big enough to affect large regions smash into Earth infrequently. The most recent example was in 1908 when an

NEO (believed to be a comet) exploded in the air over Siberia. An impact such as that occurs about once every century on average.

14. Just how many NEOs are there?

There are millions of asteroids and comets but a relatively small proportion are on a path to approach Earth. Of those, we are in most danger from NEOs with diameters in excess of 1 km that are considered large enough to cause continental- or global-scale damage.

15. What is the evidence that NEOs have collided with Earth in the geological past?

Earth and the other terrestrial planets all bear the telltale scars of past impact events in the form of craters tens to hundreds of kilometers in diameter. Impact craters are better preserved on the Moon and Mars than on Earth because these bodies lack a well-defined atmosphere. Atmospheric processes cause the disintegration of rocks on Earth's surface resulting in all landforms being worn away with time or buried under piles of younger sediment. Over 150 craters have been recognized on Earth so far.

16. What would be the consequences of an asteroid or comet colliding with Earth?

Pieces of space debris smash into Earth all the time but most are too small to survive the fall through the atmosphere. NEOs with diameters in excess of 50 meters (160 feet) are large enough to reach the surface and cause extensive damage. A large asteroid colliding with Earth would cause a series of events including a massive air blast, a giant earthquake, formation of a crater over ten times larger than the meteorite itself, the ejection of debris and gases high into the atmosphere, widespread wildfires, and a tsunami if the impact site is in an ocean. Dust and debris in the atmosphere would alter global climate, blocking sunlight to reduce temperatures in the short-term and adding greenhouse gases to elevate temperatures after the dust settles up to months or a year after the impact.

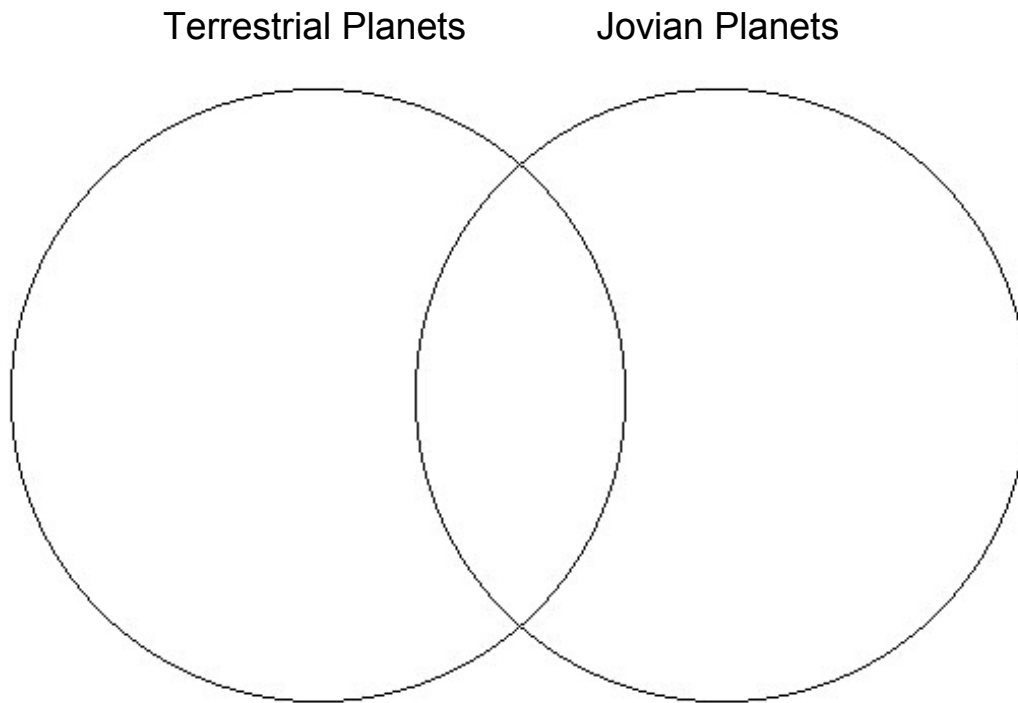
17. Why might the impact of an NEO be less of a hazard than an earthquake or volcanic eruption?

Scientists cannot calculate when an earthquake will occur and have a spotty record in predicting the timing of volcanic eruptions. However, the impact time of Earth-bound NEOs may be measured in years or decades. It is possible that the object could be deflected away from Earth or destroyed before

it enters our atmosphere. Efforts to prevent a collision would center around detonating an explosion near the NEO. At great distances, even a small nudge would be sufficient to avoid a collision but closer objects might require the explosive force of a nuclear warhead to push it off track or break it into smaller, less threatening pieces.

Venn Diagram: Terrestrial vs. Jovian Planets

Use the Venn diagram below, to compare and contrast the similarities and differences between Terrestrial and Jovian planets. Write features unique to either group in the larger areas of the left and right circles; note features that they share in the overlap area in the center of the image.



Meteorite Risk Evaluation Rubric

It is 20 years in the future. Scientists have cataloged all the largest NEOs (diameter 1 km or greater) and have found that none pose a threat to Earth. Ten years ago they began to work to identify all NEOs with a diameter of 50 meters or greater that have a trajectory that will cause them to impact with Earth. Advances in tracking technologies allow them to accurately pinpoint the location where such objects will strike the surface of the planet. So far they have found four asteroids that will collide with Earth.

Governments from around the world have contributed to an international fund to support a mission to destroy the most dangerous of the four objects. You find yourself working on a team to try to deal with the consequences of these potential collisions. Your team is charged with choosing which NEO to target for destruction first.

You are given the assignment to create an evaluation rubric to evaluate relative dangers from the four asteroids. You must find a method of ranking the risk of potential harm from each impact event. The event that scores the highest using the scoring rubric will be the first to be targeted for destruction. One factor is included as an example in the table below, identify at least four more.

Factors	Low Risk (1 point)	Moderate Risk (2 points)	High Risk (3 points)
Diameter of asteroid	Small (less than 100 m)	Intermediate (100-250 m)	Large (more than 250 m)

Reviewing your scoring rubric you realize that some factors are more significant than others. Your team decides to double the score of the most important factor. Which do they choose? Why?

Four asteroids are described below. Use your scoring rubric to decide which to target first for destruction.

Meteorite 1: VG 549

- Date of projected impact with Earth: May 21, 2093
- Diameter of asteroid: 530 meters
- Composition: rocky rubble
- Location of impact site: Paris, France

Meteorite 2: XL 795

- Date of projected impact with Earth: December 25, 2044
- Diameter of asteroid: 80 meters
- Composition: metallic (iron)
- Location of impact site: Atlantic Ocean, 20 km (12 miles) east of North Carolina

Meteorite 3: DK 240

- Date of projected impact with Earth: February 5, 2041
- Diameter of asteroid: 220 meters
- Composition: stony
- Location of impact site: central Pacific Ocean, 2,000 km (1,250 miles) south of Hawaii

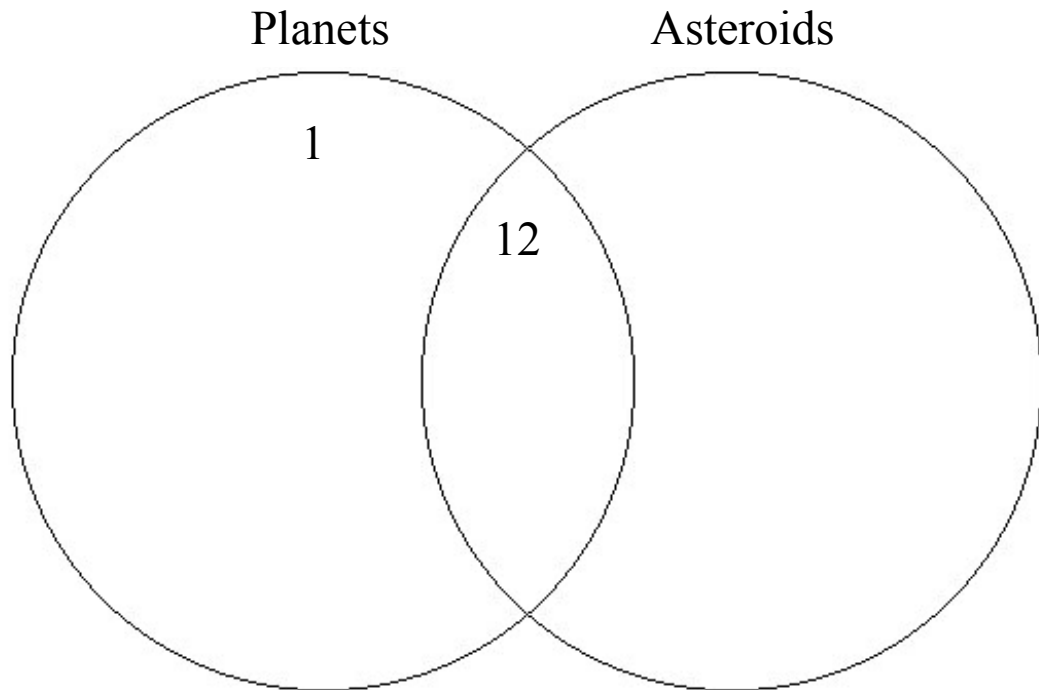
Meteorite 4: ES 097

- Date of projected impact with Earth: April 28, 2037
- Diameter of asteroid: 50 meters
- Composition: stony
- Location of impact site: Antarctica, within 300 km (188 miles) of the South Pole

Venn Diagram: Planets vs. Asteroids

Complete the Venn diagram, below, to compare and contrast the similarities and differences between planets in our solar system and asteroids.

Place the numbers corresponding to the list of characteristics below in the most suitable locations on the diagram. Two have been added as examples.



1. Radius greater than 500 km.
2. Essentially spherical in shape.
3. Orbit the Sun.
4. Have a gravitational field.
5. Rotate about an axis.
6. Made of materials similar to those found on Earth.
7. Possess moons.
8. Thousands of examples.
9. Most have atmospheres.
10. Radius smaller than 500 km.
11. Have a variety of shapes.
12. Formed after the Big Bang over 4 billion years ago.
13. Have craters.
14. Some will collide with Earth.
15. Example: Pluto.
16. Example: Eros.