Chapter 6 - The Solar System: an Overview

An isolated fact can be observed by all eyes; by those of the ordinary person as well as of the wise. But it is the true physicist alone who may see the bond that unites several facts among which the relationship is important though obscure.
--Jules Henri Poincare

Chapter Preview

In this chapter and the subsequent chapters of this section you will study the solar system and its members: the Sun, planets, asteroids, and comets. From experiments done from our one infinitesimal neighborhood of the cosmos, the Earth, humans have developed all of the physical laws that are extrapolated to the ends of the Universe. And these laws have been tested over time almost solely in our own tiny Solar System. From one star, our Sun, nine planets, dozens of moons, and countless pieces of debris left over from the origin of the Solar System (including asteroids and comets) we have obtained our knowledge of physical law, which we extrapolate to the rest of the Universe. In particular, in Section I of this book we reviewed the development of humans' understanding of the motion of two classes of objects, falling objects on the Earth and planets falling around the Sun. Then we merged the two into a Universal Law of Gravitation, which we assume holds everywhere as it does in our minuscule part of the Universe. Why? Because it is not reasonable to make any other assumption until future experience demands it. One is correct more often by assuming the simple and most likely than the complex and unlikely.

Members of our Solar System represent not only the astronomical objects in our own neighborhood, but they are our only clues left over from the origin of the solar system. One of the great problems in modern astronomy is to accurately piece together the origin of the solar system. Like a detective at a crime scene, the scientist is left with an array of clues, some relevant and some not, which can be carefully pieced together to produce a story, through the use of deductive reasoning. In this and subsequent chapters you, the jury, will be presented with the evidence. In Chapter 12 you will be led through a story of the likely origin of the solar system. It is your job to determine whether or not that this story is likely, based on the presented evidence.

This evidence has other valuable uses as well. By examining the planets we can try to determine how these bodies have evolved and will evolve over time. This is particularly valuable in trying to determine the future of our planet, including its landmasses, oceans, and atmosphere, and how changes to it will influence it future viability for supporting human life.

Key Physical Concepts to Understand: *density, the layout of the solar system*

I. Introduction

In this chapter we will begin our tour of the Solar System, starting with the Sun and working our way outward to the furthest, coldest reaches occupied by billions of unseen comets.

The Sun (Figure 1) dominates the Solar System, in terms of mass and energy. In it we can study the complex workings of an ordinary star in the middle of its estimated 10 billion year lifetime; it is the only star that can be observed close up and is therefore essential in interpreting clues gathered from the billions of other stars that can be seen in the sky.

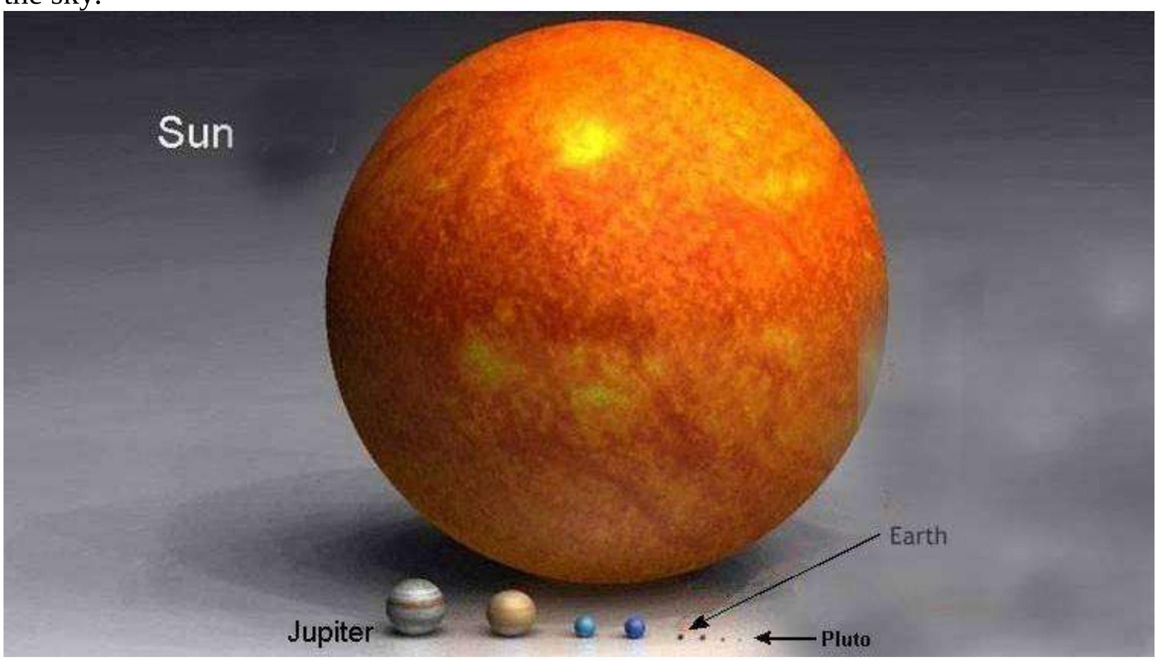


Figure 1. *Relative sizes of the Sun and planets (plus Pluto). From* http://www.physics.uci.edu/~observat/Physical_Scales.html

Table 6.1: *Orbital Characteristics of the Planets*

Planet	Distance from Sun		Orbital Period
Mercury	0.39 AU	58 x 10^6 km	0.24 years
Venus	0.72	108	0.62
Earth	1.00	150	1.00
Mars	1.52	228	1.88
Jupiter	5.20	778	11.86
Saturn	9.54	1427	29.46
Uranus	19.19	2871	84.01
Neptune	30.06	4497	164.79
Pluto	39.53	5914	248.54

Table 6.2: *Physical Characteristics of the Planets*

Planet	Diameter		Mass		Density
Mercury	4,878 km	0.38 D_{Earth}	3.3 x 10^{23} kg	0.06 M_{Earth}	5430 kg/m^3
Venus	12,100	0.95	4.9 x 10^{24}	0.81	5250
Earth	12,756	1.00	6.0 x 10^{24}	1.00	5520
Mars	6,786	0.53	6.4 x 10^{23}	0.11	3950
Jupiter	142,984	11.21	1.9 x 10^{27}	317.94	1330
Saturn	120,536	9.45	5.7 x 10^{26}	95.18	690
Uranus	51,118	4.01	8.7 x 10^{25}	14.53	1290
Neptune	49,528	3.88	1.0x10^{26}	17.14	1640
Pluto	2,300	0.18	1.3x10^{22}	0.002	2030

The Solar System carries 99.86% of its mass in the Sun. Of the rest of the mass, 80% is contained in Jupiter, and less than 1% is in our Earth and Moon system. The Solar System can be viewed as a massive central star, encircled by a small amount of debris left over from its formation including nine planets (Figures 2 & 3), their moons, billions of smaller chunks of ice – comets, and tens of thousands of smaller chunks of rock – asteroids.

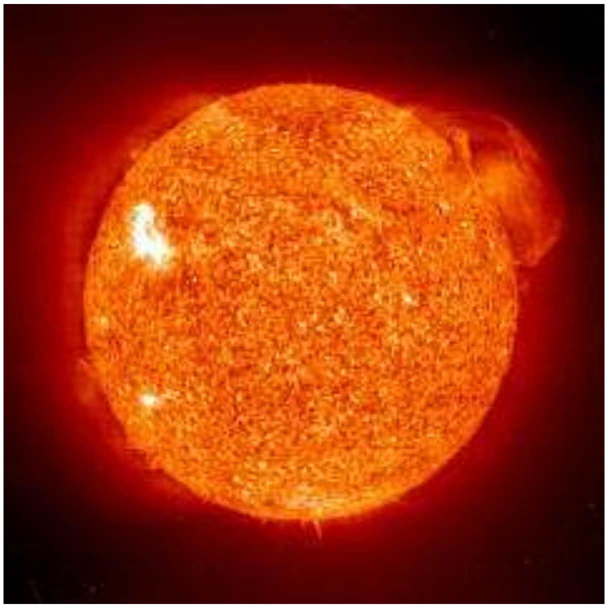


Figure 2. *The Sun.*

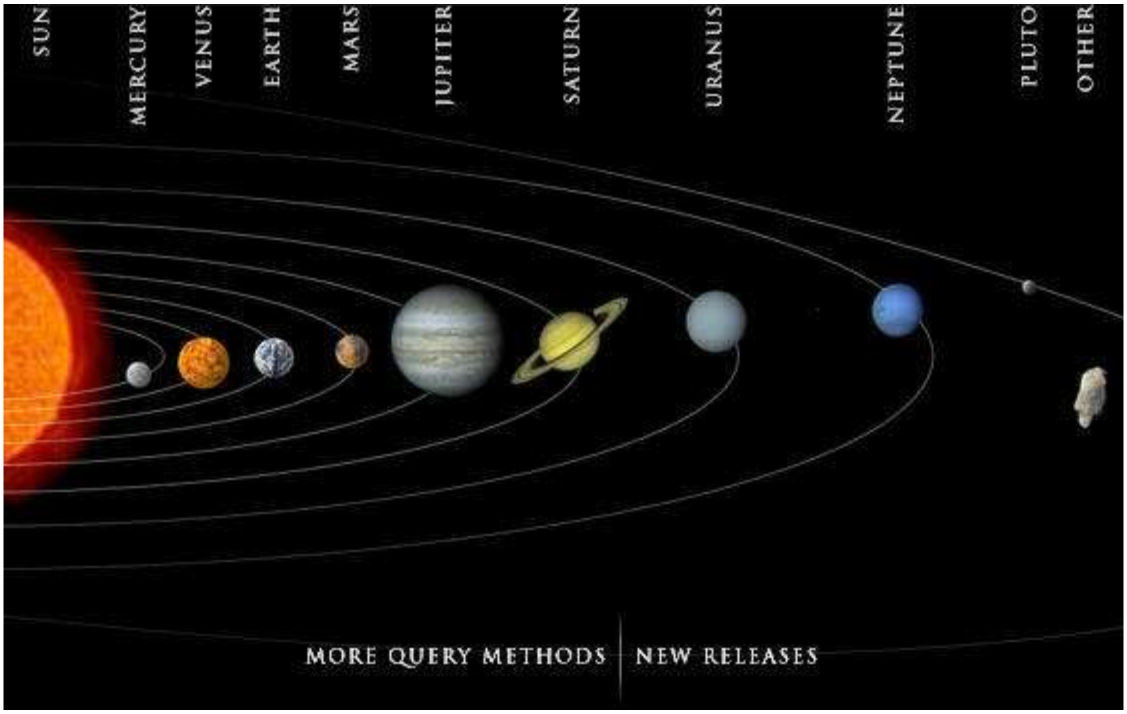


Figure 3. *Scale of the Solar System: relative distances. Sizes are not to scale. NASA.*

The word "planet" comes from the Greek word "planetai" or wanderers, for the Greeks observed that the planets were nomads, wandering against the background of stars. While the stars in the night sky move in unison, due to the combined rotation and revolution of the Earth, the planets follow this general motion but with their own peculiar motion superimposed.

The planets orbit the Sun, controlled by its gravity, in elliptical orbits as modeled by Kepler's laws. Although the orbits of the planets are found, on average, in a single plane, called the plane of the ecliptic, there are deviations. The Earth's orbit, for example, is tilted by 14° with respect to the ecliptic. When the Earth finds itself high above or below the ecliptic plane, the inner planets, Mercury and Venus, do not cross directly in front of or behind the Sun, but are seen to pass above or below it.

The nine planets can be divided into two groups. The four innermost planets have solid surfaces – Mercury, Venus, Mars, and the Earth – and are called the terrestrial planets (Figure 3). The four giant outer planets – Jupiter, Saturn, Uranus, and Neptune – are composed mainly of the light elements hydrogen and helium, and exhibit no evidence of a solid surface (Figure 4). The latter are referred to as the gas giants or **Jovian** (after Jupiter or Jove, the Roman king of the gods and ruler of the Universe) planets. Pluto, as we shall see, doesn't cleanly fit into either category.

Figure 3. *The terrestrial planets (NASA). Can you identify each of them?*

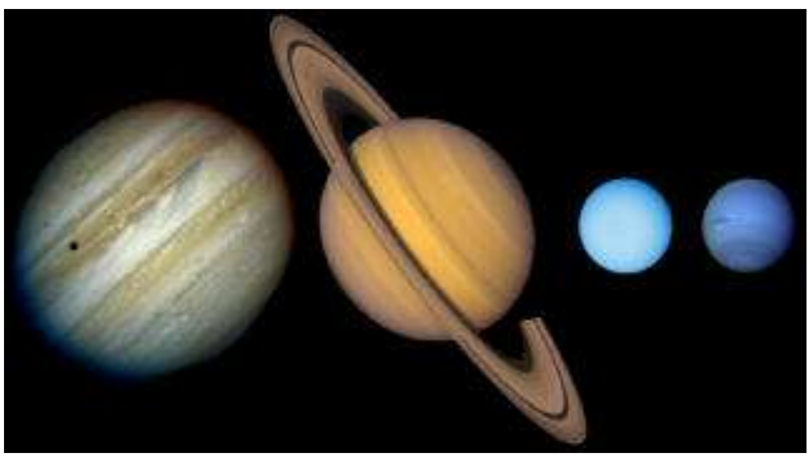


Figure 4. *The gas giants (NASA). Can you identify each of them?*

WebVideo: Scale of the Planets and Their Satellites and a Tour of the Solar System
https://www.khanacademy.org/science/cosmology-and-astronomy/v/scale-of-solar-system

The planets can be described by several properties, three of the most important of which are mass, size, and density. Density is the mass of an object divided by its volume. For planets, the density varies inside the volume of the planet. The Earth for example has a dense core and a not-so-dense crust. When we talk about the density of a planet we usually refer to the **average density**:

Equation 6.1: Average density = mass of the entire object / volume of the entire object

In metric units, density is expressed as grams/cubic centimeter (g/cc) or kilograms/cubic meter (kg/m^3). Density is a good indicator of the composition and physical properties of the material making up an object. Water for example has a density of 1000 kg/m^3 (1 g/cc). The average country rock on the Earth has a density of 3000 kg/m^3 (3 g/cc). Iron has a density of 8000 kg/m^3. The Earth has an average density of 5500 kg/m^3, much higher than the rocks found on its surface. This tells us that the composition of the interior of the Earth is quite a bit different than its crust.

The four inner planets have densities that are substantially higher than water, between 3900 kg/m^3 and 5500 kg/m^3. The four outer planets have densities that are much lower than the inner planets, from 690 kg/m^3 for Saturn to 1640 kg/m^3 for Neptune. These data support the notion that the compositions of the planets also fall into two groups, the rocky terrestrial planets, and the gas giants, composed of hydrogen and helium. Pluto is an exception, a small planet with a solid surface, like the terrestrial planets, but a low density of 2000 kg/m^3, closer to a gas giant than a terrestrial planet.

II. Mercury

Mercury, the innermost planet, has a highly elliptical orbit extending from 28 million miles (45 million kilometers) to the Sun at closest approach, outward to 43 million miles (69 million kilometers), with an orbital period of only 88 days. One Mercury day is actually longer than its orbital period, with 90 Earth days of sunlight followed by 90 Earth days of darkness. These extremely long periods of light and darkness result in extremes in surface temperature, freezing cold days followed by smoldering 1000° F days. The mass of Mercury, $1/18^{th}$ that of the Earth, is comparable than that of several of the moons, or satellites, of other planets. An astronaut on Mercury would find that the gravity is only $3/8^{th}$ of the Earth's surface gravity, with an escape velocity also only $3/8^{th}$ of the Earth's. That would make it easy to launch a spacecraft from the surface of Mercury. That has also made it easy for any gas molecules in its atmosphere to have boiled off the planet, heat from the nearby blazing sun having pushed them to velocities exceed the 2.6 miles/second escape velocity of Mercury

III. Venus

The surface of Venus is enshrouded in an opaque veil of yellow-white sulfuric-acid clouds. It wasn't until the 1960s that the rotational period could even be determined; this was accomplished using radar signals bounced off the surface to time the appearance and disappearance of mountains and valleys. It is now known that Venus has a rotational period of 243 Earth days, longer than its orbital period of 224.7 days and it the opposite direction of the rotation of the other planets. It is normal for the planets to orbit the Sun and spin on their axes in the same counterclockwise direction, as viewed from far above the North Pole of the Sun. An astronaut on Venus would experience 118 days between sunrises, with perpetually overcast skies. Venus is considered Earth's twin in many respects, with a mass 0.81 of the Earth's, a thick atmosphere, and a density of 0.93 of the Earth's. However, it is completely inhospitable to life with a surface temperature of 536° F, hot enough to melt lead. What has led a similar and relatively close neighbor to a completely different set of surface conditions? Will the Earth be led to a similar fate? These are some of the questions that will be asked when we study Venus in Chapter 9.

IV. Earth and Moon

The Earth and Moon form a double planet system with the Moon having a diameter one-quarter that of the Earth. Their surfaces are a study in contrasts. The Moon has a lifeless monochromatic surface with no envelope of atmosphere or ocean. Much of its surface is saturated with craters from a past episode of intense bombardment of space debris, chunks of rocks and ice left over from the formation of the Solar System. The Earth is a planet of great complexity, its surface in a constant state of alteration, the result of intricate interactions between its geologically active surface, its dense atmosphere, and its oceans. Earth is the only planet in our Solar System that has conditions that are known to be adequate for the development and support of life. As dissimilar as the Earth and Moon are, the Moon represents the Earth as it was, some 3 billion years ago, before its surface was altered by processes such as volcanism and atmospheric erosion, processes that have not occurred in a significant way in the last 3 billion years of the Moon's evolution.

V. Mars

Mars is known for its nomination as "planet most likely to succeed in harboring life", other than the Earth. Its solid surface, atmosphere, and climate made, and perhaps still make it a logical candidate for the discovery of extraterrestrial life. At a distance of 142 million miles (228 million kilometers) from the Sun, Mars is a relatively small planet with a mass one-tenth the mass of Earth and a surface gravity close to that of Mercury's. It has a thin atmosphere composed of carbon dioxide and trace amounts of water. The mean Martian temperature is -60° F. In the winter the temperature is low enough to solidify atmospheric carbon dioxide as solid dry ice, seen deposited every winter as a thin layer on the Martian polar caps, sublimated into atmospheric carbon dioxide again in the spring. A Martian day is 24.5 hours long; a year is 687.5 Earth days. Other than the Earth, Mars is the only terrestrial planet with moons; it has two moons, Phobos and Deimos, only 10 miles and 5 miles in diameter.

VI. Asteroids

There is a huge gap between the orbit of Mars and Jupiter occupied only by the asteroid belt, a zone containing rocks from the size of small moons, down to boulders, pebbles, and fine dust (Figure 5). Over 6,000 of the asteroids having sizes of 1 kilometer to 1000 kilometers in diameter have been observed long enough for orbits to have been determined. Tens of thousands of asteroids larger than 1 kilometer are thought to inhabit the asteroid belt.

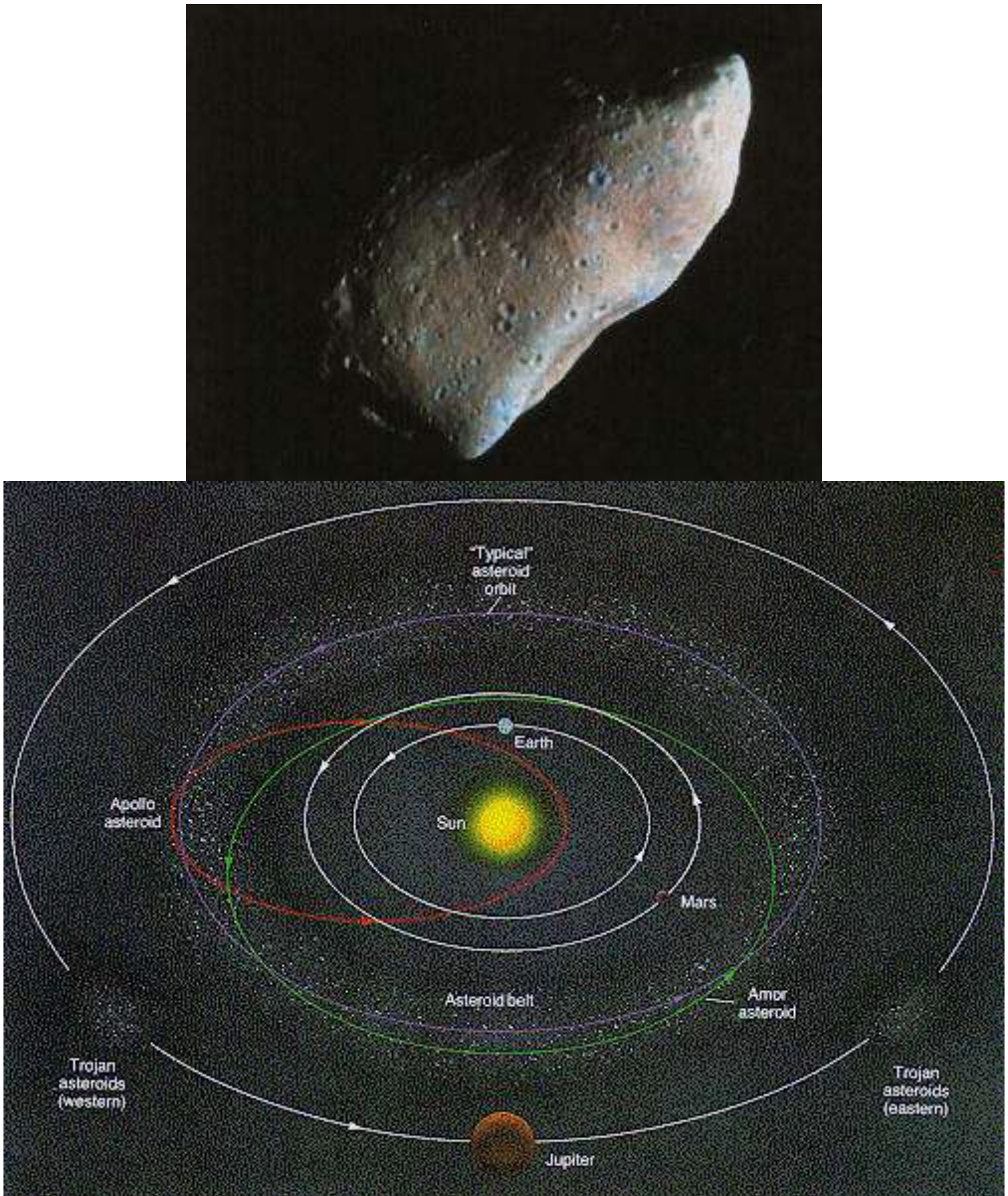


Figure 5. *A. The asteroid Gaspra. NASA. and B. Asteroid belt.*

VII. Jupiter

At five times the distance of the Earth from the Sun lies Jupiter, the behemoth of the planets, 1300 times the volume of the Earth. Jupiter boasts 90% of the mass of all of the planets, although it has only one-quarter of the density of the Earth. This low density is a result of a chiefly gaseous composition; Jupiter is composed almost entirely of the light gases hydrogen and helium, with surface clouds of methane and ammonia ice crystals. Cloud patterns in the upper atmosphere produce alternating bright and dark bands on the surface, as well as spiral-shaped cyclonic cloud patterns.

Jupiter rotates with a 10-hour period, carrying its equator along at a dizzying speed, resulting in a bulging equator. The polar diameter of Jupiter is $15/16^{th}$ the equatorial diameter because of this "centrifugal flattening."

Jupiter is accompanied by an array of 16 satellites, two of which are bigger than our Moon. Jupiter and its moons orbit the Sun once every 11.9 years.

IIX. Saturn

Saturn, the second largest of the gas giants, has a mass 95 times that of the Earth, but a density only 0.7 times that of water. At a distance twice that of Jupiter's from the Sun, it has a year of 29.5 Earth years. Like Jupiter, it has a spin period of 10 hours and 14 minutes, resulting in an equatorial bulge. Saturn is known for its distinctive rings, constituting billions of pebble to boulder sized rocks and ice chunks orbiting Saturn's equator in a thin ring, perhaps remnant of a stillborn moon. Saturn has an entourage of 17 satellites. One, Titan, is as large as Mercury and carries a substantial atmosphere.

IX. Uranus

While the Earth and the other five planets closest to the Sun were known to the ancients, the others were discovered after the invention of the telescope. Uranus was discovered in 1781. Uranus has a mass of 14.5 Earth masses and is accompanied by five satellites. This gas giant has a rotational period of 10 hours and 49 minutes and an orbital period of 84 Earth years. Uranus is distinguished by a ring system, not as substantial as Saturn's, and a spin axis that is tilted by 98 degrees out of its orbital plane (remember that the Earth's axis is tilted 23.5 degrees out of its orbital plane). The result is that the Uranian North Pole is pointed toward the Sun for half of its orbital period, and away from the Sun for the other half. This means that the North Pole sees 42 years of continuous sunlight and 42 years of continuous darkness.

X. Neptune

At a distance of 2.8 billion miles from the Sun lies Neptune. Neptune was discovered 60 years after the discovery of Uranus, based on observed deviations of the orbit of Uranus, not exceeding two minutes of arc. From Newton's laws the position of Neptune was predicted, and it was subsequently discovered. Neptune has two satellites; one is larger than our Moon and closer to Neptune that our Moon is to the Earth.

XI. Pluto and Charon

Pluto was discovered in 1930, after a reported deviation in the orbit of Neptune from an unseen planet. There is still some controversy as to whether Pluto's position was predicted or it was actually discovered by accident. Pluto is slightly larger than Mercury. It has a highly eccentric orbit that takes it to within 2.7 billion miles at closest approach to the Sun (inside the orbit of Neptune) to a maximum distance of 4.6 billion miles. Pluto orbits the Sun once every 248 years, and possesses a single satellite, Charon. The mean surface temperature of Pluto is -370 F, cold enough to freeze nitrogen from a gas to a solid on its surface.

XII. Comets

Outside the orbit of Pluto, the solar neighborhood, out to the nearest stars at a distance of about 3 light years, 189,000 A.U., is occupied by an estimated 100 billion comets, in the orbital plane of the planets and in a roughly spherical swarm above and below the orbital plane of the solar system (Figure 6). At large distances from the Sun, comets are small, 1 to 10 kilometer diameter, chunks of methane- water-, and ammonia-, ices, mixed with dust in a low-density froth. Occasionally the passage of star through the solar neighborhood disturbs the orbit of a comet, sending it on a journey into the inner part of the solar system. Approaching the inner Solar System, light and particles emanating from the Sun boil gas and dust off the fragile, easily vaporized solid surface. The resulting gas forms a fog around the nucleus, some of which is pushed back millions of miles by sunlight and solar particles to form an enormous tail of insignificant density, stretching across the inner solar system. Occasionally a comet will collide with a planet, scaring its surface with an impact crater. The terrestrial planets are all covered with the remnants of such impacts. One is thought to have impacted the Earth with such violence that it resulting in the extinction of the dinosaurs.

Figure 6. A. Comet Hale Bopp. Brian Rachford . and B. The Oort comet cloud.

Key Words & Phrases

1. **average density –** the total mass of a body divided by its volume
2. **Jovian -** Jupiter-like. The Jovian planets in our Solar System are Jupiter, Saturn, Uranus, and Neptune.

Review for Understanding

1. Summarize the distinctive features of each of the planets.
2. Why is Uranus smaller than Neptune is, but more massive?

Essay Questions

1. Build a scale model for the Solar System using a beach ball for the Sun, and appropriate sized balls (e.g., tennis ball, golf ball, baseball, etc.) and fruits or vegetables for the planets. Report your results. Then, determine how far these objects would have to be separated in order to maintain this scale.

Chapter 7 - The Earth: a Planetary Perspective

All that man knows of cosmic law he has learned in the thin shell of life's domain, the rock-floored, air-vaulted observatory in his natural spaceship.
--David Bergamini, *The Universe*

Chapter Photo. *Image of the daytime hemisphere of planet Earth from space, taken from Apollo 17 in December 1972.* FMW 148-7.1.

Chapter Preview

The Earth is key in our study of the other planets in the solar system and in answering the fundamental geological questions: How old is the Earth? How did the Earth originate? How is the Earth evolving? Scientists are going a long way in answering these same questions for the solar system as a whole. Surely, the origin and evolution of the Earth must be linked to the origin and evolution of the other planets. Earth can be examined in much more depth, breadth, and detail than any other planet. In this chapter we will review what we know of the Earth as a planet – its interior, surface, oceans, and atmosphere – and use this picture as a reference from which we can draw conclusions from observations of the other planets. When planets have similar properties we infer that these properties stem from like causes. When they differ, this spurs us to dig further for evidence of the underlying cause of this difference. Although you will read about the Earth's structure and the physical processes supporting that structure in this chapter, theories of origin and evolution of all the planets, and other members of the solar system, will not be presented until Chapter 13. Then all the pieces of evidence, i.e. information about all the members of the solar system, will be reviewed and examined as a whole.

Key Physical Concepts to Understand: *radioisotope dating, coriolis, seismic waves, plate tectonics, differentiation, greenhouse effect, Earth's chemical and physical structure, Earth's atmospheric composition and structure*

I. **Introduction**

Imagine how the Earth would appear to visiting alien astronaut/scientists, viewing the planet for the first time. Since Earth scientists have only been able to detect planets outside our solar system in the last few years, and no further details outside simple detections have yielded themselves to observation, we can only guess at the uniqueness of the properties of our Earth, or at the existence of intelligent life elsewhere. But certainly aliens, having studied the Earth for some length of time, would find it the most uniquely complex and dynamic planet in our solar system, at the very least. It is unique in possessing an oxygen-rich atmosphere which supports life, unique in being covered (almost three-quarters of its surface) by liquid water oceans and icy polar caps, unique in its rapidly altered landforms – mountains and valleys continuously constructed and then obliterated by wind and rain and corroded by its atmosphere, unique in its shrinking and crumpled crust, covered by cracks and fissures punctuated with volcanic mountains, like beads on a string (Figure 1). Earth is a richly complex planet, its parts are the source of numerous fundamental areas of study, including geology, geophysics, meteorology, atmospheric science, and oceanography. Here we will only be able to summarize those properties that are relevant to the study of the other eight planets of our solar system.

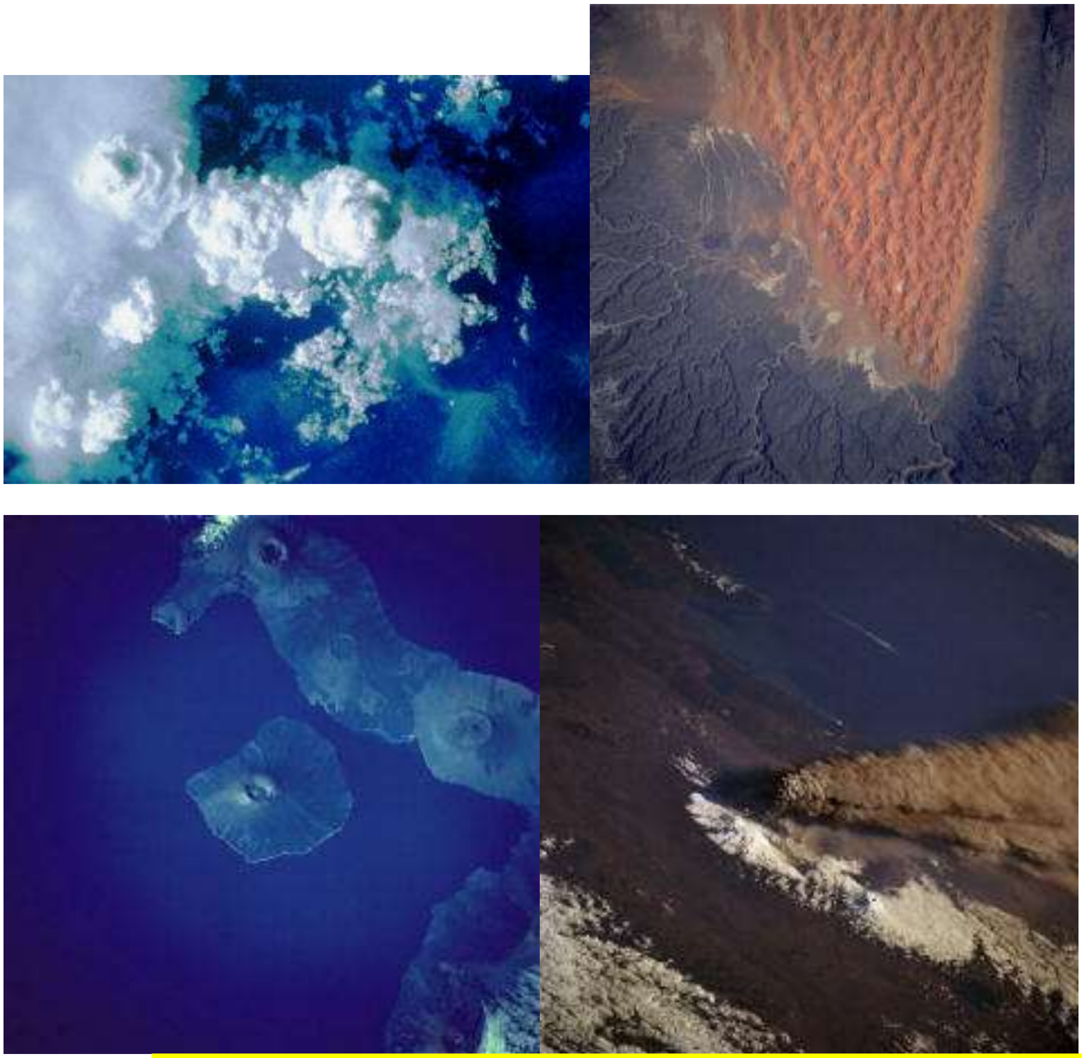


Figure 1. *Earth remote sensing collage. Upper left, clockwise: volcanic plumes, sand dunes in the Sahara Desert, snow capped mountains, and volcanic islands. NASA.*

II. **Gross Properties**

Table 7.1: *Bulk Properties of the Earth*

Property	Measurement
Mass	6.0×10^{24} kg
Radius	6378 km
Average Density	5520 kg/m^3
Average Distance from the Sun	149.6×10^6 km
Orbital Period	365.26 days
	1 year
Orbital Eccentricity	0.017
Rotational Period (w respect to the Sun)	24.0 hours

A. Shape of the Earth

Although Eratosthenes was the first to measure the Earth's circumference in about 200 BC, the Earth's spherical shape was not directly observed until Magellan's circumnavigation of the globe in 1522. More recent measurements show that the Earth is not precisely spherical, but its diameter measured from pole to pole is 43 kilometers less than its equatorial diameter. In 1680 Newton explained this as a centrifugal effect; a rotating Earth would naturally produce an equatorial bulge if the material out of which the Earth is made were not completely rigid. This flattened spherical shape is called an **oblate spheroid.**

B. Earth's Rotation

The Earth's rotation seems subtle enough to us, as we are carried along with the Earth's surface it appears stationary. However some of its effects are as dramatic as its departure from sphericity. At the equator the Earth's circumference is approximately 40,000 kilometers. The spinning Earth moves this 40,000-kilometer equator once every 24 hours. Its velocity is then 40,000 kilometers/24 hours or 1700 kilometers/hour. As the Earth spins about a rotational axis intersecting its poles, the rotational poles have no velocity resulting from rotation. Latitudes between the poles and equator move at some intermediate velocity. This latitude-dependent velocity is responsible for the clockwise and counterclockwise cloud and weather patterns seen on in the Earth's atmosphere (Figure 2).

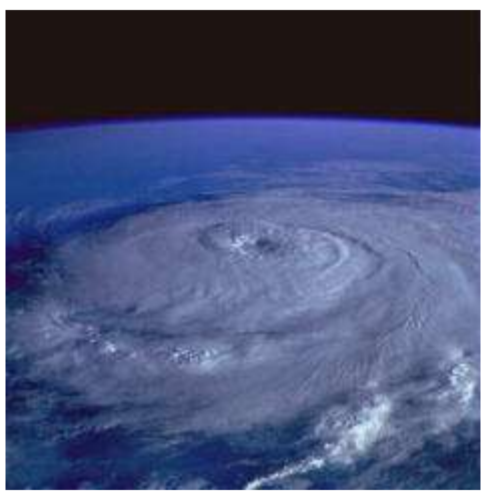


Figure 2. *Hurricance Elena in 1985. From donasdays.blogspot.com*

If the Earth had no nights without solar insolation, was covered only by land, had no mountains or depressions, and was not rotating; its weather patterns would be much less complex. Without the effects of topographic features, rotation, and the rising and setting of the Sun, air at the Equator would be warmed, would rise into the upper atmosphere (warm air rises as a result of its lower density compared to cold air), and flow to the poles

(Figure 3). Air at the poles would cool, increase in density, sink in altitude, and flow back to the Equator.

A rotating Earth changes this picture dramatically. The spinning Earth causes a deflection of moving air by the **coriolis effect** (Figure 4). As the Earth rotates from west to east, it carries its atmosphere along with it. Air at the equator is also moving from west to east at about 1700 kilometers/hour (the land speed for a vehicle is 410 mph or 660 kilometers per hour). As this air is warmed and moves toward the poles, although slowed a little by friction with the surface, still it is moving from west to east faster than the land under it. As a result, this pocket of warm air will appear to move toward the east with respect to the underlying land as it heads north. Air moving north appears deflected to the east. Air moving to the South Pole will also appear to move toward the east with respect to the Earth's surface. This is the coriolis effect.

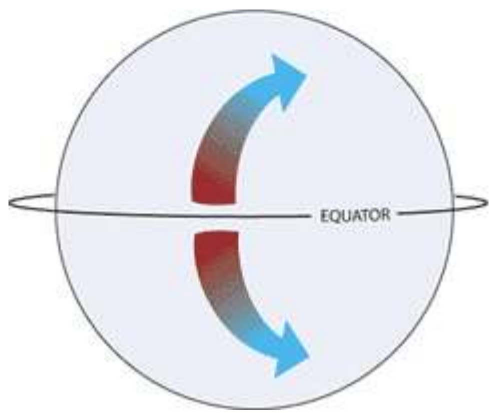


Figure 3. *The coriolis effect. Because of the Earth's rapid rotation (right to left in this figure), air moving from the rapidly rotating equator to the stationary poles is deflected toward the right. This is called the coriolis effect. NOAA.*

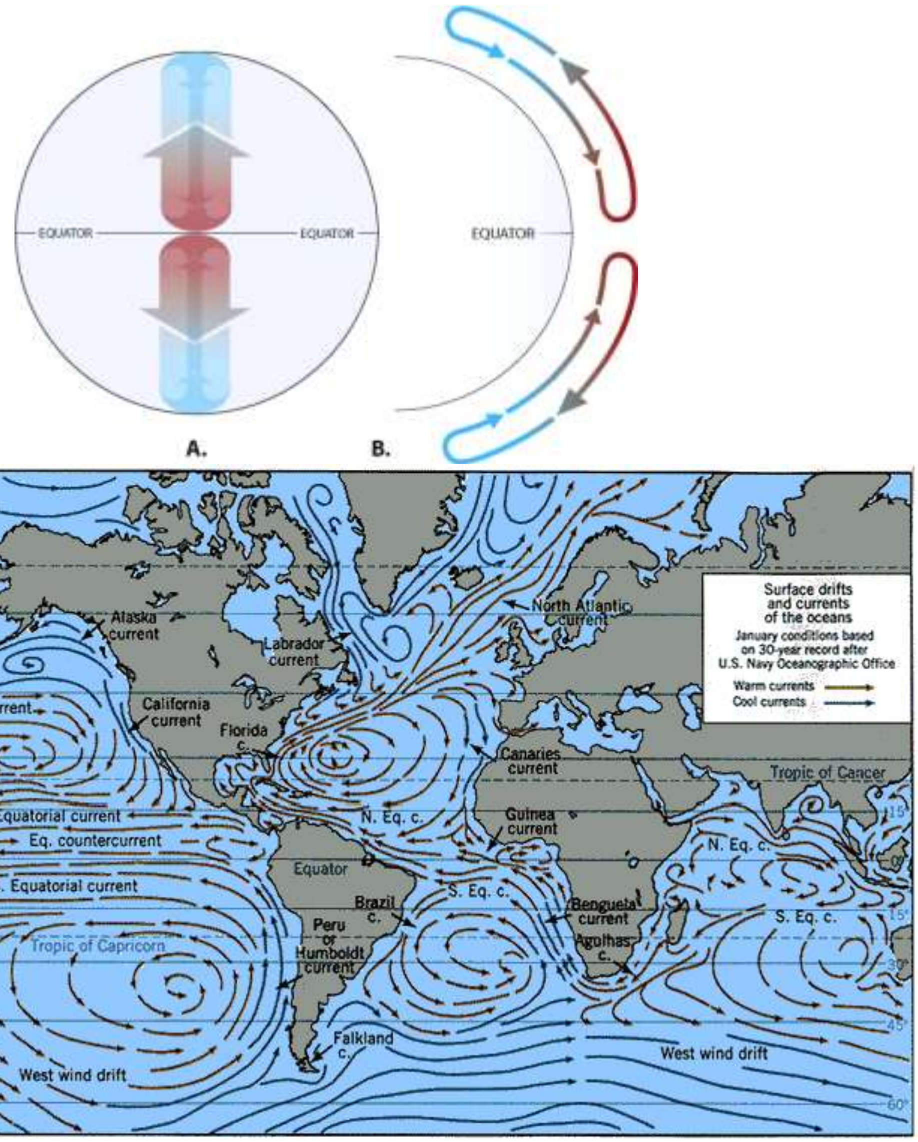


Figure 4. *Coriolis.* ***Panels A&B.*** *For a non-rotating Earth, air warmed at the equator would rise and flow directly along a meridian toward the poles where it would cool, sink and flow directly along the meridian toward the equator.* ***Panel C.*** *Because the Earth rotates, Coriolis causes ocean currents in the Northern Hemisphere circulate in a clockwise direction; in the Southern Hemisphere currents circulate in the counterclockwise direction. NOAA.*

This effect is reversed as air returns from the poles headed toward the equator. Air sitting at the poles carries no component of velocity from the Earth spinning under it. As it heads toward the equator, from either the North Pole or the South Pole, the underlying Earth will be spinning from west to east, leaving this pocket of air behind. For an observer attached to the spinning Earth, a mass of air moving from pole to Equator will lag behind them, so it will appear to be moving from east to west. So, air moving from Equator to pole is deflected to the East; air moving from pole to Equator is deflected to the West. The result is that low pressure weather systems in the Northern Hemisphere appear to spin in a counterclockwise direction, and in the Southern Hemisphere appear to spin in a clockwise direction.

WebVideo: the Coriolis Effect http://www.youtube.com/watch?v=aeY9tY9vKgs

The coriolis effect is significant enough that it is taken into account by the military in the use of long-range artillery. If the gun on a battleship near the equator is fired at a vessel 10 miles away and coriolis is not taken into account, the artillery shell will miss its intended target. Coriolis is not the predominant effect in determining the direction in which water drains in a sink or bathtub, contrary to folk wisdom. Water in a sink or bathtub has a slow but significant residual rotation determined largely by how the water was last disturbed. Even pulling the plug on a bathtub will disturb the water and induce a small net rotation in it. As the sink or bathtub is drained and water enters the drain, the volume of water spins faster and faster as it is funneled into the narrow drainpipe. As a result the initial rotation of the water is amplified, with whatever direction it initially had. As an experiment, you might drain your tub a few times and note the spin direction. (To complete the experiment you will need to fly to South America.)

III. **How Old is the Earth?**

The age of the Earth is certainly one of its most fundamental properties and a subject of controversy since humans first attempted to assign an age to our planet. In the 17th century, biblical scholars attempted to determine the Earth's age by following the genealogy of humankind outlined in the Bible, from Adam and Eve. Naturally this method depended on a literal interpretation of the Bible as well as a host of other assumptions. Nevertheless, in 1650 Archbishop James Ussher of Ireland, declared that the Universe was formed on Sunday October 23, 4004 BC, and humanity was created on Friday the 28th. This result was soon disputed by geologists who observed the depth of sediments deposited at river mouths and inferred that at the current rate of deposition they would take more than ten thousand years to form. Thus began the debate between scientists and some literal interpreters of the Bible that continues even today. In the 17th century the geological/religious debate was just as controversial as the biological/religious debate was in the early 20th century. Archbishop Ussher and his followers argued that the contradicting geological evidence was planted by the devil to subvert believers. This argument provides vivid illustration of the difference between religion and science. Both are systems of belief. Religious belief is based on faith; scientific belief is based on evidence. Science is not able to answer questions for which no evidence exists, for example, "Who or what created the Universe?" The answers to such questions are necessarily limited to the realms of theology and philosophy. In order for an hypothesis or theory to be a scientific one, it must be capable of being proven false. It is not possible to disprove that the devil placed false and misleading evidence on the Earth to mislead believers, therefore it is not a scientific hypothesis, but a theological or philosophical proposition. But non-scientific hypotheses do not lead to new scientific discoveries of the world around us and are outside the scope of this book. We will only discuss them as they illustrate the scientific method.

A more scientific method of dating the Earth waited for the discovery of radioactivity by the French scientist Antoine Becquerel in 1896. Radioactivity is the result of unstable nuclei of atoms, which spontaneously give off one or more particles on route to becoming a more stable nucleus.

The nucleus of an atom is composed of two types of fundamental particles, protons and neutrons (Figure 5). Both particles have approximately the same mass, but while the proton carries a positive unit of electric charge, the neutron carries no charge. The number of protons and neutrons determines the mass of the nucleus, but the number of protons alone determines how many orbiting electrons will accompany the nucleus and how the resulting atom will interact and combine with other atoms. Thus only the number of protons will determine how we identify a nucleus as an element. For example, an atom of helium must always have two protons in the nucleus, independent of the number of neutrons. A nucleus with two protons and one neutron is a helium nucleus (called helium-3 because it has an atomic mass of three nuclear particles). A nucleus with two protons and two neutrons is still a helium nucleus (helium-4); although its mass is different than that of helium-3, all helium atoms are chemically interchangeable. Nuclei with the same number of protons but a different number of neutrons are called **isotopes** of the same element.

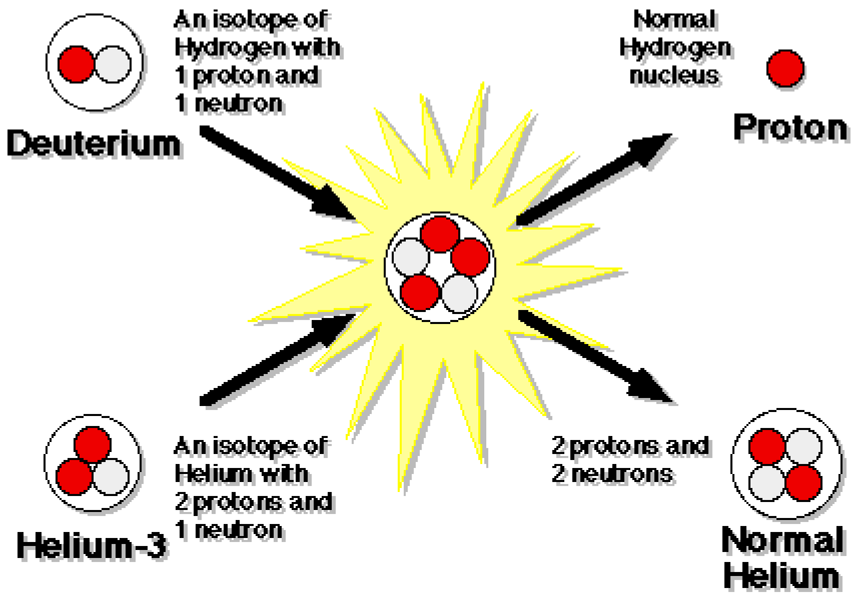


Figure 5. *A schematic diagram of the atomic nuclei of hydrogen-1, deuterium (hydrogen-2), helium-3, and helium-4. Hydrogen-1 and deuterium are isotopes of the same element as are helium-3 and helium-4.*

A radioactive, or unstable, nucleus can decay into an isotope of the same element or, in a bit of radioactive alchemy, into a completely new nucleus of differing proton number. The product of such a radioactive decay is called the **daughter nucleus**; the original atom is the **parent nucleus** (Figure 6). This decay process is purely statistical in nature. Given a single unstable nucleus it is not possible to predict with any accuracy whether it will decay tomorrow or in one million years. Given a sample of a large number of identical nuclei, say billions of nuclei, it is possible to predict accurately when one-half of them will decay into daughter nuclei. This time for half of any sample to decay to daughter nuclei is called the half-life of the unstable nucleus. It is possible to use the slow decay of radioactive nuclei as a clock to date the formation of rocks containing those nuclei.

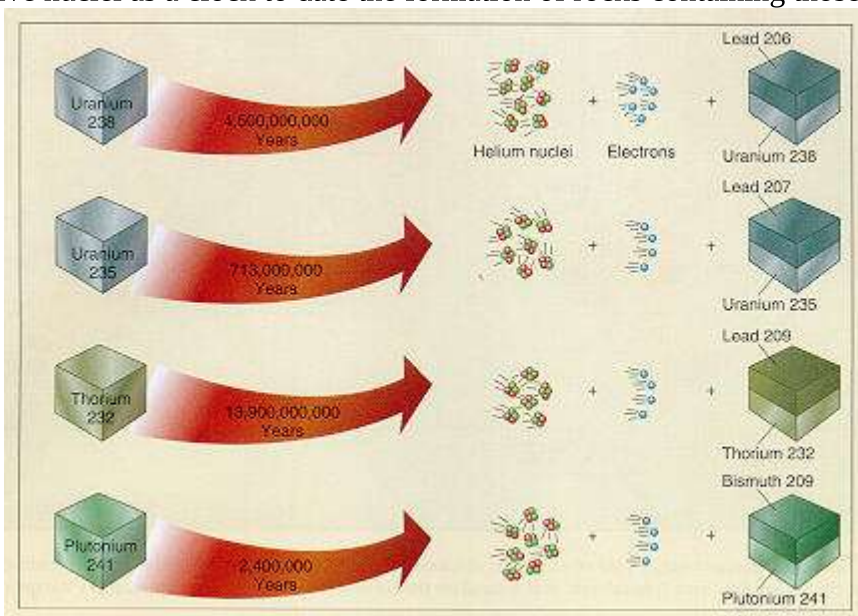


Figure 6. Radioactivity cartoon. *The radioactive decay of 1 gram of Argon-39 to Argon-38. Shown are the amounts of mother and daughter isotopes after 1 half-life, 2 half-lives, and three half-lives.*

Radioactive Dating

Before we look at radioactive dating it is important to understand the statistical nature of radioactive decay. Because decay is statistical in nature, the half-life does not depend on the sample size or the prior history of the sample. For a single nucleus with a half-life of one year that hasn't yet decayed, the probability is 50% that the nucleus will decay in one year. The nucleus has no memory. If we come back in one year and the nucleus hasn't yet decayed, and you ask me, "What is the probability that this nucleus will decay within the next year?" my answer will be the same, 50%! It is much like flipping a penny (an honest one), which also has no memory. The odds of obtaining tails are 50%. If I flip tails five times in a row, what are the odds of flipping odds on the sixth coin flip? They are still 50%. While such odds seem useless for single coin flips and single nuclear decays, their power expresses itself with large numbers of events. If I flip a coin 100,000 times, it is clear that I should very nearly obtain 50,000 heads and 50,000 tails. Similarly, if I have a gram of Uranium 235 with a half-life of 713 million years, I know that after 713 million years I will have 0.5 grams of U-235 and 0.5 grams of its daughter, Lead-207. Does all of the U-235 disappear in two half-lives? No. Since the nuclei have no memory, after another 713 million years have passed one-half of the remaining 0.5 gram of U-235 will have decayed, leaving 0.75 grams of Pb-207 and 0.25 of U-235. Note that one cannot specify how long it will take all of the atoms to decay any more than one can say with certainty how long it would take any individual nucleus to decay.

One simple example will be used to illustrate the power of dating using radioactive isotopes. Argon-39 is an unstable nucleus, which radioactively decays by emitting a neutron producing the stable Argon-38 nucleus. The half-life of this decay is 260 years. Argon is a gas that is itself produced by the radioactive decay of the element Krypton. Since argon is a gas, any argon detected in a rock had to have been produced after the rock was last in a molten state. Any subsequent melting of the rock would allow the argon to bubble to the surface and escape. The ratio of Argon-38 to Argon-39 therefore tells us the age of the rock since the matter in the rock last cooled from the molten state, assuming that this occurred more than once. Rocks generally have more than one set of radioactive parent-daughter nuclei, so there are opportunities to check the results of different radioactive dating reactions against each other.

WebVideo: Radioactive Dating http://www.youtube.com/watch?v=AepDyWBStqo

The results of radioactive dating rock samples on the Earth yields wildly differing ages. Rocks in the Rocky Mountains are generally less than 60 million years old, the Appalachians are a few 100 million years old, Hudson's Bay in Canada is a few billion years old, and individual specimens in Greenland are found to be over 3.9 billion years old. These wide variations in age from place to place as well as in neighboring locations, and sometimes in different crystals in the same rock, are testament to the processes that resurface the Earth: wind and water erosion, volcanic eruptions, sedimentation, and chemical oxidation among others. From dating other, more unaltered solar system rocks, from the Moon and the meteoritic debris floating between the planets, it is thought that the Earth and other planets were formed about 4.6 billion years ago.

IV. **Earth's Interior**

What is the structure of the Earth's interior (Figure 7)? We know that the Earth's core must differ considerably from its outer skin; rocks at the surface have densities of about 3000 kg/m^3 while the mean density of the Earth as a whole is 5520 kg/m^3. There is almost no direct evidence of the Earth's interior. The deepest sample of the Earth's interior is from a Siberian oil well, which has retrieved rock samples at a depth of less than 15 km. Some rocks in South Africa originate from 400 to 500 km, brought up by volcanic processes. Even these samples represent a layer of only the uppermost 5% of the Earth's skin.

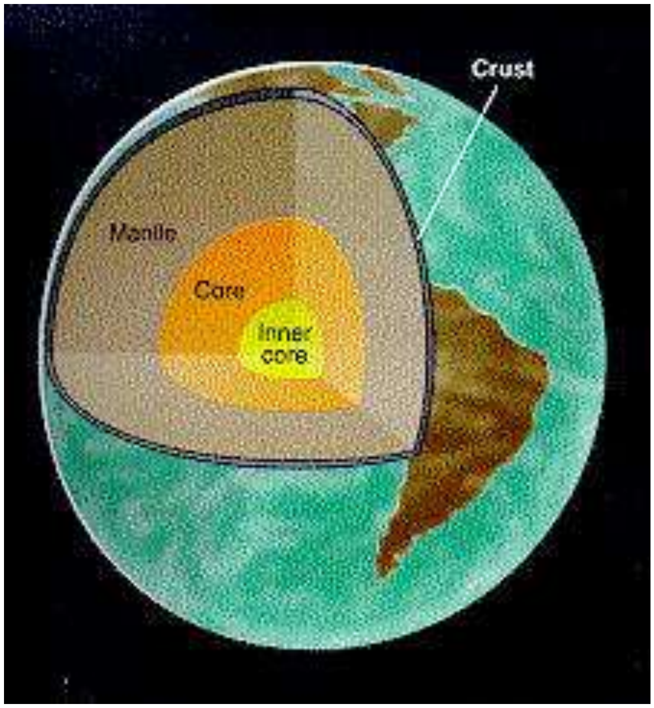


Figure 7. *A schematic diagram of the Earth's interior.* FMW 149-7.2.

Seismic waves, or earthquake vibrations, from deep within the Earth have been used to produce low resolution images of the Earth's interior, somewhat like sonic images are made of babies inside the mother's womb (Figure 8). Seismic waves are bent or absorbed by the Earth according to its composition, density, and whether or not it is in a solid or liquid state. For example, one kind of seismic wave does not travel through liquid. When a number of seismic detectors spread around the globe detect earthquake vibrations, a quiescent molten core is seen silhouetted against a background of seismic activity. Seismic measurements have yielded a layered picture of the Earth's interior, with layering due to both chemical and physical properties.

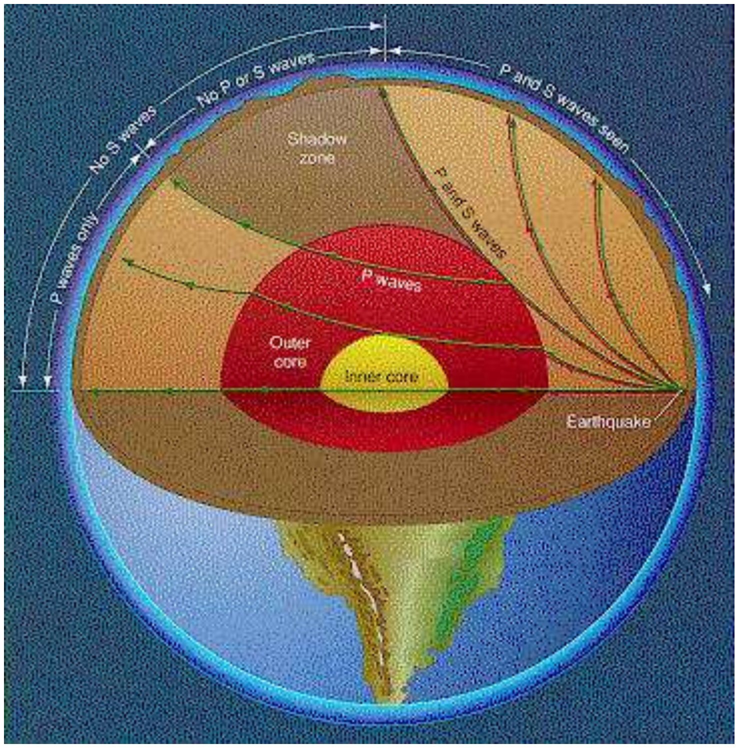


Figure 8. *Seismographs produce an image of the Earth's interior. Earthquakes generate two types of waves, pressure waves, P-waves, and shear waves, or S-waves, which can be detected by seismographs around the globe. S-waves do not travel through liquid, and therefore silhouette the Earth's molten iron core.*

A. Layering According to Chemical Composition

Models of the Earth from seismic data give us a picture of the Earth with three layers of differing chemical composition. The Earth contains a high-density core of nickel-iron, an intermediate density rocky mantle, and a low-density rock crust. Early in its history, the Earth is thought to have been totally molten, as a result of the explosive impacts of coalescing debris that formed the Earth as well as heat generated from radioactively decaying nuclei in the Earth's interior. As in any mixture of liquids, the high-density material was pulled to the center of the Earth by gravity, the low-density material floated on the top. This gravitational separation of materials in a planet according to their density is called **differentiation**.

The core of the Earth has a 3500-km radius. The density of the core is 10,000 to 12,000 kg/m^3 indicating that it is composed of a nickel-iron alloy, or mixture. While the outer core is hot and molten, pressure would keep the inner core a solid nickel-iron sphere.

The mantle of the Earth extends from a depth of a few tens of kilometers beneath our feet to the core-mantle boundary at a depth of over 2800 kilometers. Mantle rocks, like surface rocks, are composed of silicon-oxygen compounds called silicates. **Quartz and ordinary beach sand are composed of silicon dioxide crystals, or crystals with one silicon atom for every two oxygen atoms.** The density of silicate rocks depends on the relative amount of heavier elements, like iron and aluminum, added to the crystal structure. Earth's mantle contains silicates of higher density, approximately 6000 kg/m^3, containing significant magnesium, iron, calcium, magnesium, and aluminum abundances.

The upper layer of the Earth's surface is a skin varying in thickness between five and thirty kilometers depending on location (Figure 9). The oceanic crust is only about five kilometers thick, made up of high-density, iron and magnesium-rich silicates called basalts, having a mean density of about 3000 kg/m^3. The continental crust is up to 30 kilometers thick at its thickest, in the middle of the Earth's mountain ranges, made of iron-poor, low-density silicates called granites, having a mean density of 2700 kg/m^3. Although most of the high-density elements, such as iron, have sunk to the Earth's center, they are not completely absent from the Earth's crust owing to their chemical attraction, in relatively small portions, to compounds in the crust.

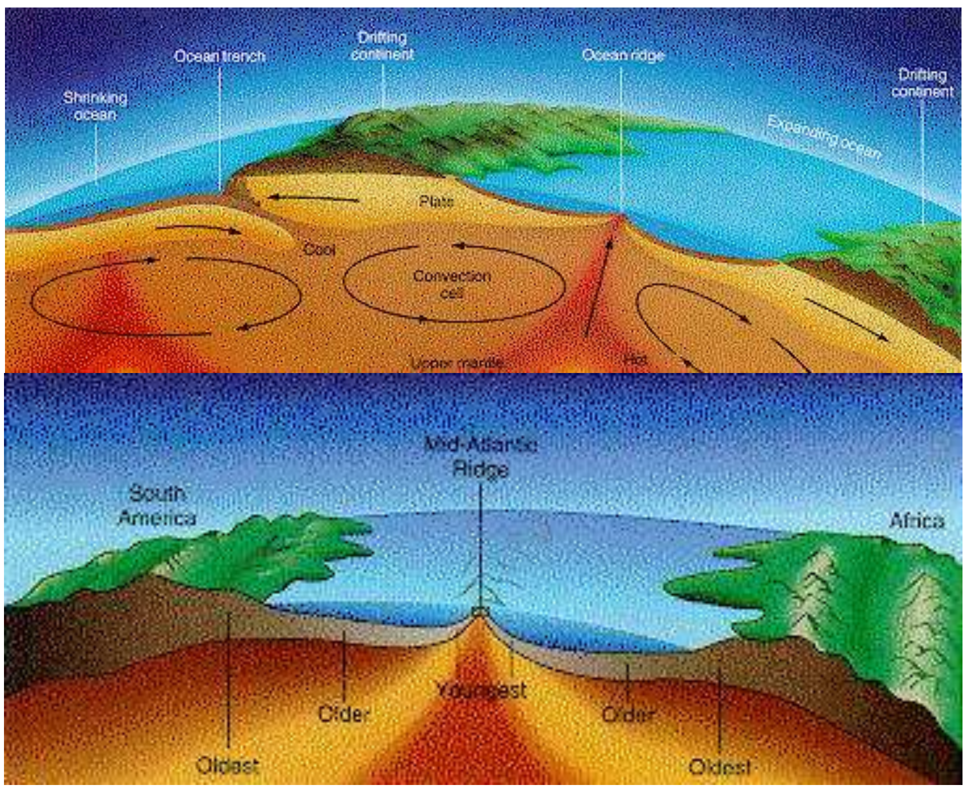


Figure 9. Panel A. *The Earth's continental and oceanic crustal plates are pushed together or pulled apart by convection currents in molten mantle. Radioactive heating of the Earth's interior drives convection.* **Panel B.** *Mid-oceanic ridges, such as the mid-Atlantic ridge are formed by two oceanic plates being pulled apart. Material from the Earth's molten mantle oozes up at the mid-oceanic plate boundary, forming new crust to replace the departing plates.*

B. Layering According to Rigidity

At the time of formation, the Earth is thought to have been nearly completely molten. Subsequently, it has cooled by radiating light energy (in the infrared part of the spectrum) into space from its surface. As the surface cools the center slowly conducts heat to the surface, replacing, in part, the energy that has been radiated away. This is the same process that we observe in food just removed from the oven, baked potatoes for example. A recently baked potato will be much hotter in the center than at the surface. We should therefore expect the Earth to be much hotter in the center than at the surface, with the Earth's temperature increasing with depth. The Earth is approximately 290 K at its surface, rising to about 5000 K at its center. Earth is cooling very slowly because of its enormous size; it continues to generate energy due to the radioactive decay of elements such as uranium and thorium, and an insulating crust that covers it.

The rigidity of the Earth varies with depth according to its temperature and composition. The outer, coolest part of the Earth's crust and upper mantle is made of relatively rigid, brittle rock. This layer is called the **lithosphere** from the Greek for "rock sphere" (Figure 10). Under the lithosphere is a semi-solid layer of rock that is warm enough to deform or slowly flow, like asphalt on a hot day that retains the tread pattern from the car parked on it for a long time. This deformable or plastic layer is called the **aesthenosphere**, from the Greek for "weak rock". The lower density lithosphere literally floats on the asthenosphere.

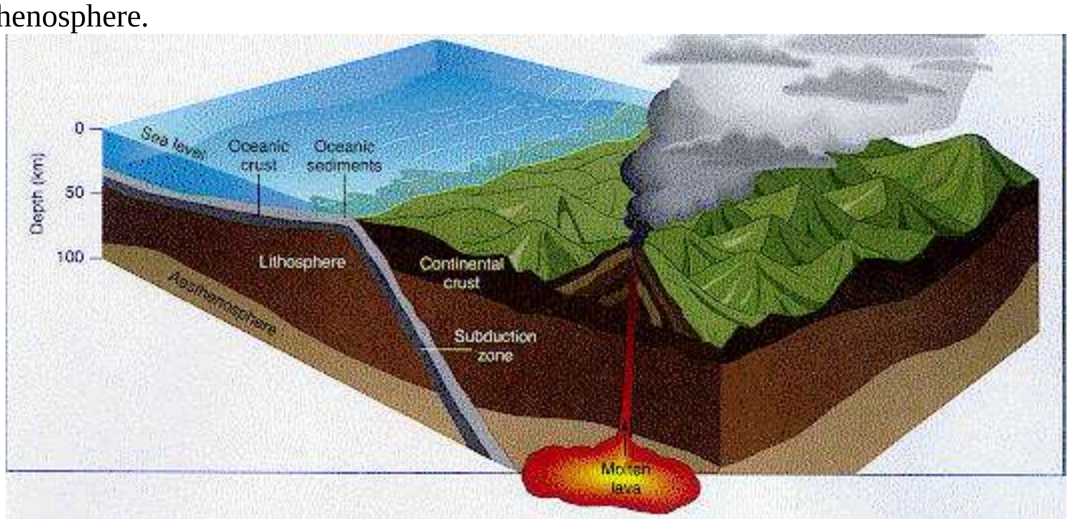


Figure 10. *The upper portion of the Earth can be divided by the composition and density of the rocks into the lower density crust and higher density mantle or the solid lithosphere, comprising crust and upper mantle, and molten aesthenosphere, the soft, fluid part of the mantle. The thick continents and thinner oceanic crust float on the underlying aesthenosphere. When two plates crash together, one rides on top of the other, buckling the Earth's crust and producing a folded mountain range.*

V. **Plate Tectonics**

In 1620 Francis Bacon, the noted English philosopher and scientist, noted that the shapes of the continents were such that it looked like they would fit together like pieces to an enormous jigsaw puzzle. South America would nestle into the crook of western Africa, while the Atlantic coastline of Canada would slide against western Europe. There was no other data to support the unity of the Americas with Europe and Africa.

In 1912 Alfred Wegener, a German meteorologist, greatly expanded on Bacon's idea by proposing a theory of **continental drift** (Figure 11). Wegener based his theory on rocks deposited by glaciers that were discovered in India, Australia, South America, and India, indicating that these regions were at one time much colder and were possibly located much closer to the South Pole. Fossil ferns found in North America indicated that it was once much closer to the equator. Wegener's theory was ridiculed at the time, for it was hard to conceive of an energy source that would move entire continents across the Earth.
Wegener's theory of continental drift didn't receive significant support from the scientific community until the 1960's when enough evidence had accumulated to support his theory, including two important discoveries. One was the discovery of an underwater mountain range, the Mid-Atlantic ridge, which runs North-South through the middle of the Atlantic Ocean, through both Northern and Southern Hemispheres (Figure 12). The youngest rocks on this ridge are found along its middle. The crustal rocks get older the farther one moves from the ridge. This is consistent with new crust being formed along the center of the ridge. The other was the discovery that rock types matched between the coastlines of the Americas, Europe, and Africa, as if Bacon's original hypothesis were correct. These discoveries led to a more comprehensive theory of the motion of continents over the Earth's surface, now called **plate tectonics**.

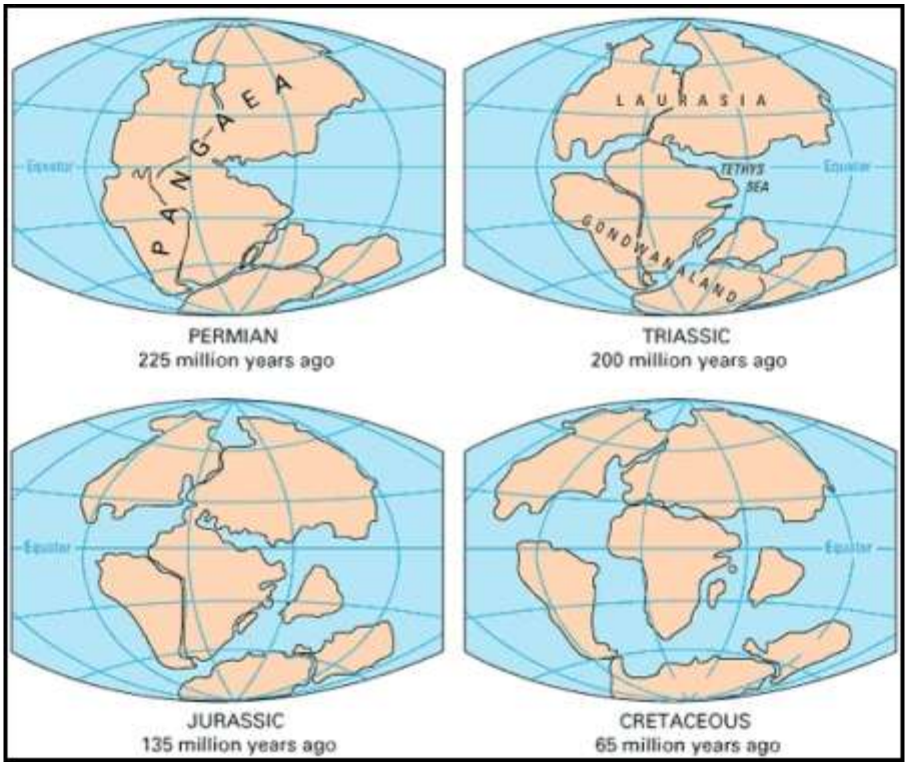


Figure 11. *From the measured motion of the Earth's tectonic plates, it is possible to estimate their positions millions of years in the past. 200 million years ago the Earth's solid surface was composed of one super-continent, called Panagaea. From* [*www.paralleldivergence.com*](http://www.paralleldivergence.com)

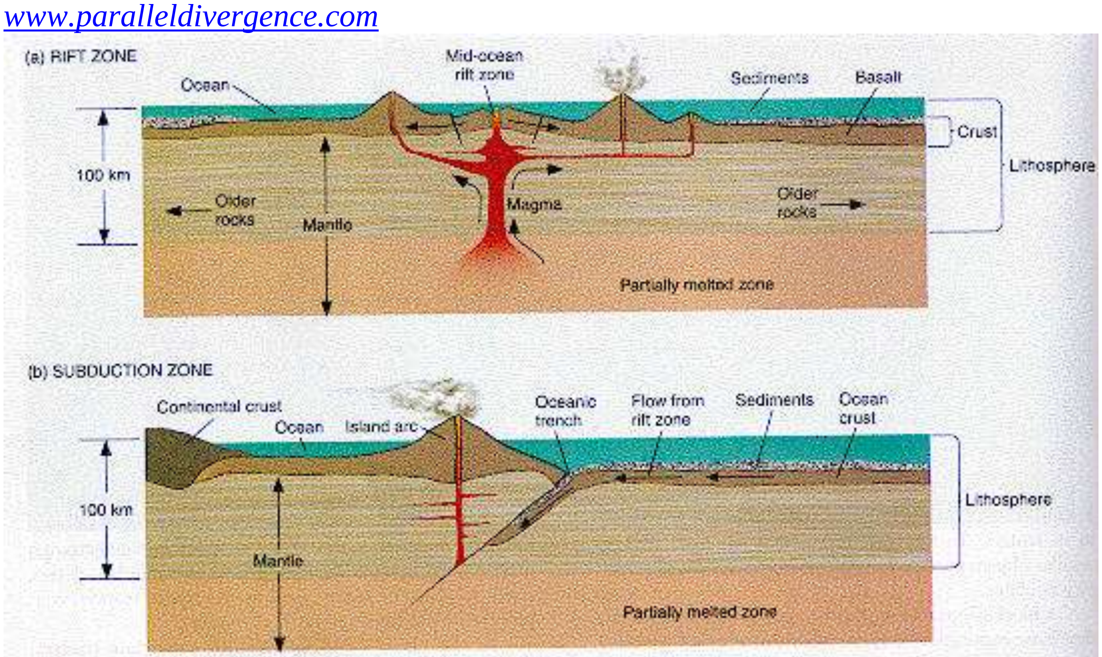


Figure 12. The structure of the Earth at plate boundaries. **Panel A.** *At plate boundaries where two tectonic plates are separating, a gap is formed through which magma flows, forming new crust. This is how the mid-oceanic ridges are formed.* **Panel B.** *Where two*

tectonic plates crash together, one is forced into the mantle under the other. A trench and folded mountains are formed along the boundary. **FMW 152-7.7.**

Geologists now generally believe that the engine that drives continental drift is the heat produced in the Earth's interior that is following outwards toward the surface. Just as heat from a stove can produce **convection** cells of motion in a pan of water heated to a "rolling boil", material in the Earth's asthensophere is in constant, although slow, motion. Heated silicates deep in the Earth's mantle expand and float to the surface where they release heat energy to the surface, subsequently cooling and sinking. These most-or-less-circular convection motions push and pull the Earth's brittle crust, causing it to fracture, separate, and move at rates of several centimeters a year.

WebVideo: Convection [**http://www.youtube.com/watch?v=07ENtC42rrw**](http://www.youtube.com/watch?v=07ENtC42rrw)

When centers of major earthquake and volcanic activity of the last several decades are plotted on a map of the Earth (Figure 13) it is seen that they do not randomly cover the globe, but are located along specific geographic boundaries. It is believed that these boundaries represent boundaries of eight or so large continuous plates of lithosphere floating on the underlying and convecting asthenosphere. At the plate boundaries, plates are either separating, sliding against each other, or crashing into one another. These movements produce sporadic and local releases of energy in the form of earthquakes as the crust moves in spurts. Volcanic flows also preferentially take place at plate boundaries as subcrustal magma oozes up from depth erupting onto the surface of the Earth.

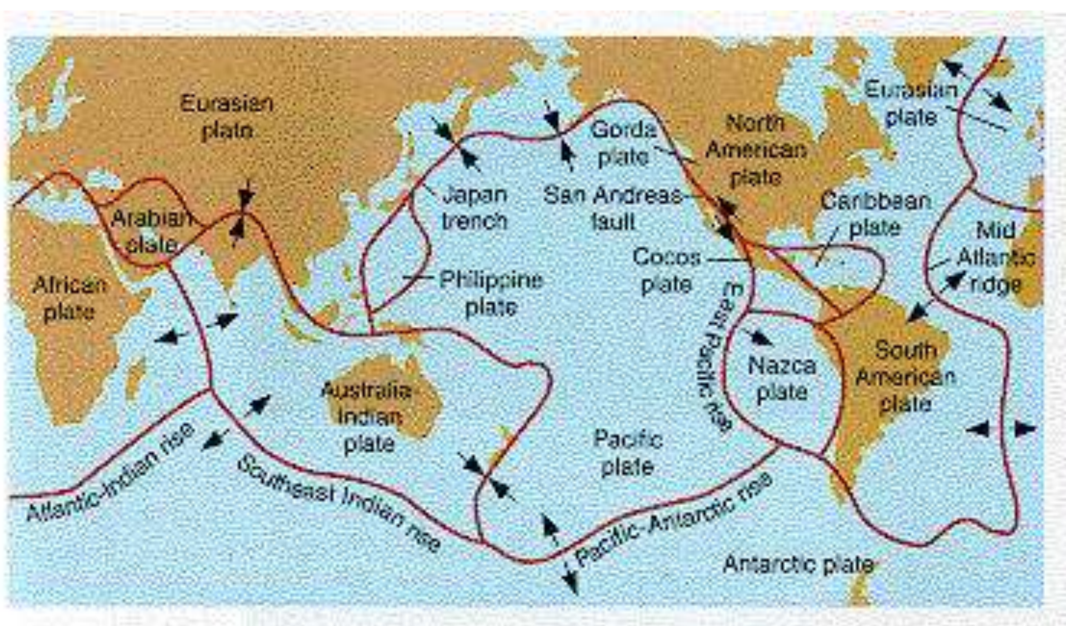


Figure 13. *The major tectonic plate boundaries which separate the Earth's crust. Arrows show the direction of motion for each of the plates.* **FMW 151-7.6.**

The Mid-Atlantic Ridge formed as the North American plate and South America plate moved westward and separated from the Eurasian plate and the African plate. As these continents separated and continue to separate today, new crust is formed at the plate boundaries from magma seeping up from depth. On the Pacific side of the North American plate, the Pacific plate is ramming into the North American plate. The Pacific plate causes the North American plate to be thrust upward, forming mountain ranges (called folded mountain ranges, as opposed to volcanic mountains) along the Pacific coast of North America. The eastern part of the Pacific plate is devoured as it slides under the North American plate at the plate boundary. As the Pacific plate loses crust at its eastern edge, the North American plate is being added to at its eastern edge. The result is that the Earth's surface is simultaneously moving and being repaved over hundreds of millions of years.

Motion of the Earth's surface is being measured by scientists on a global scale. If one uses the current rates of continental drift, typically 2 centimeters/second/year, and extrapolates backward into the past, the continents were joined as one immense supercontinent about 300 million years ago.

WebVideo: Plate Tectonics http://www.youtube.com/watch?v=KCSJNBMOjJs

VI. **Why Does the Earth Have a Magnetic Field?**

Magnetic force is the force generated by moving charge, e.g. an electric current in a wire. Magnetic force can also be produced in an apparently static bar magnetic. On a microscopic level, however, even the bar magnet is not static. Each iron atom in a bar magnet has currents produced by electrons orbiting its nucleus, as does any solid bar. In most solids such orbits are randomly aligned, as any magnetic force produced by one atom is canceled by the opposite magnetic force from its neighbor. In some materials, known as magnetic materials, such as iron, it is possible to align the atoms by magnetizing the material with another magnet. (You can magnetize a steel paper clip by rubbing one pole of a bar magnet along the length of the paper clip, repeatedly, but in one direction only.) The net result is the cumulative effect of a huge number of tiny magnetic forces, each due to the current of a charge orbiting an iron nucleus.

WebVideo: the Earth's Magnetic Field
http://www.youtube.com/watch?v=wDAlHQJ4u80

The Earth has a magnetic field similar to that of a bar magnet (Figure 14), with one pole located near, but not coincident with, the Earth's North rotational Pole, the other near the South rotational Pole. The Earth and a bar magnet both produce a **field** of force surrounding them. **A field is simply a spatial variation of a parameter throughout a volume. A magnetic field is the variation of magnetic force throughout a volume of space.** The Earth's gravity pulls on us everywhere we stand, although it becomes weaker for astronauts above the Earth's surface. This pull of gravity can be thought of as the Earth's gravitational field.

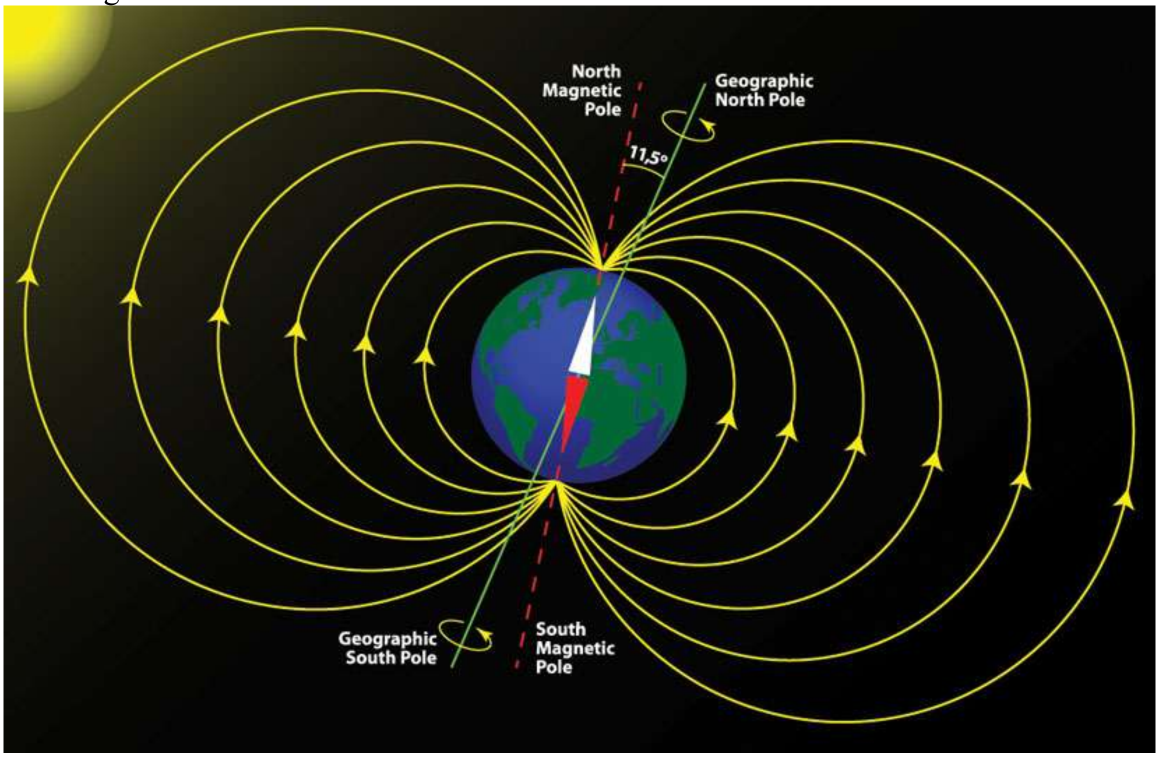


Figure 14. *The magnetic field of Earth. The volume surrounding the Earth is filled by the Earth's magnetic field. This diagram indicates the direction of magnetic force in this field, the same direction that a compass would point. From* *http://news.discovery.com/earth/zooms/earth-magnetic-field-poles-flip-fast-121024.html*

A bar magnet suspended in the Earth's magnetic field feels the magnetic force from the Earth, so that its north pole is attracted to the North Pole of the Earth and its south pole is attracted to the South Pole of the Earth. The result is a compass: the north pole of the compass will always point toward the North Pole of the Earth.

How is the Earth's magnetic field produced? If an electric current produces a magnetic field, then what is the source of the electric current in the Earth? It is believed that the Earth's molten core is a magnetic dynamo, powered by the rotation of the Earth and the convective motion in its electrically conductive nickel-iron core. This phenomenon is not well-understood, but the rotational and convective motions somehow produce electrical currents which produce a magnetic field that is nearly aligned with the Earth's rotation axis. It *is* known that a planet with a solid iron core can not produce a magnetic field.

The Earth's magnetic field protects life on Earth from the dangerous high-energy particles boiled off the Sun's atmosphere, called the **solar wind**, which continuously impact the Earth (Figure 15). Such particles, like ultraviolet light, are dangerous because they can damage our genetic material, causing skin cancer. The magnetic field serves as a barrier to charged solar wind particles that are trapped high about the Earth by the Earth spiraling in its magnetic field. During periods of intense solar activity, when particles overload the magnetic field, they spiral in the magnetic poles, colliding with gas molecules in the upper atmosphere. The collisions cause gas molecules to emit light, which in turn produce the spectacular colored light displays that we call **aurorae.**

WebVideo: Aurorae http://www.youtube.com/watch?v=FcfWsj9OnsI

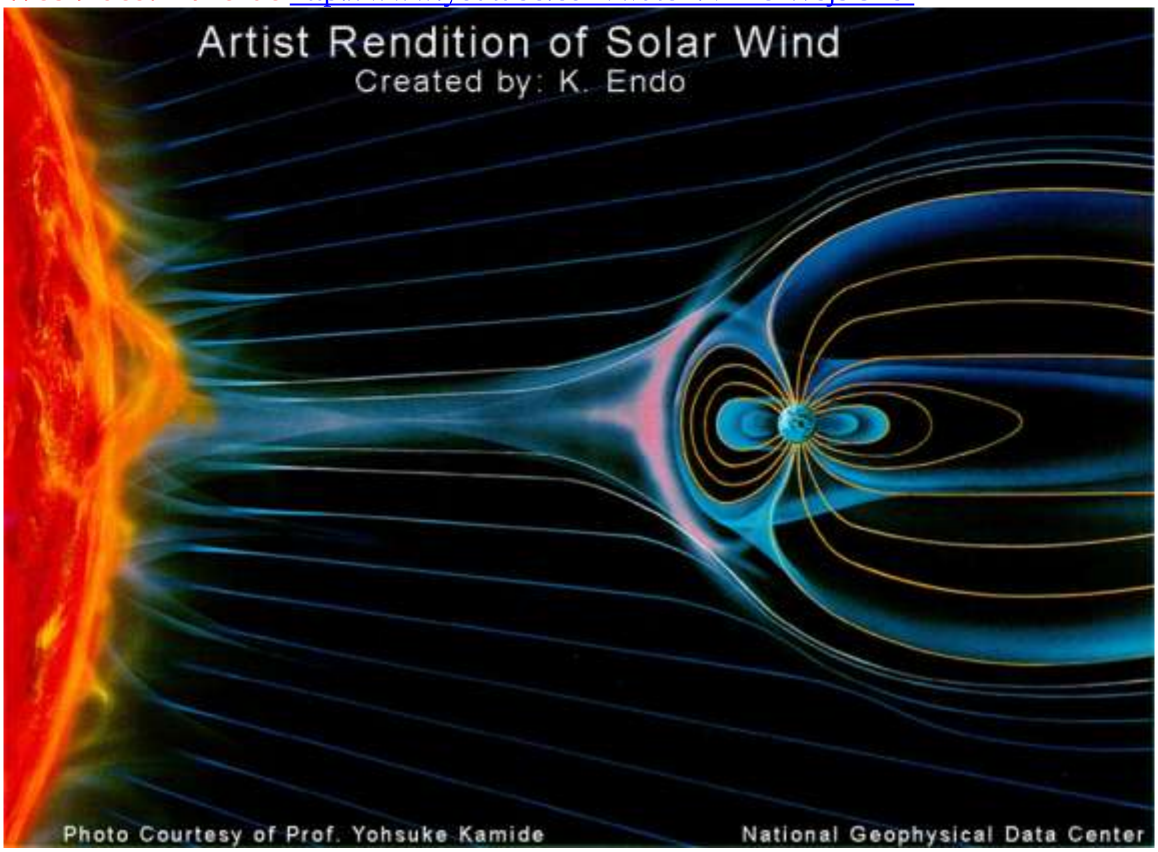


Figure 15. *Solar wind, particles escaping the Sun and colliding with the Earth's magnetic field. Not to scale.*

VII. **Earth's Atmosphere and Oceans**

A. Atmosphere

The atmosphere of the Earth is extremely important both geologically and biologically. From a geological perspective it modifies the surface of the earth physically, by erosion from wind and water, and chemically, by oxidation and other forms of chemical alteration. The Earth is characterized by the most active atmospheric landform modification of the planets in our solar system. As a result, there are few ancient rocks or remaining examples of the impact cratering which occurred early in the Earth's history.

The Earth's atmosphere is gravitationally bound to its surface, which retains all gaseous molecules moving at less than the Earth's escape velocity (Figure 16). The velocity of an atom or molecule is proportional to root $\sqrt{T/m}$, where T is the temperature (in K) and m is the relative mass of the atom or molecule. The result is that an atmosphere which at either high temperature or containing light gases, loses molecules into space.

WebVideo: Atmospheric gas escape velocity.
http://m.teachastronomy.com/astropedia/article/Why-Giant-Planets-are-Giant

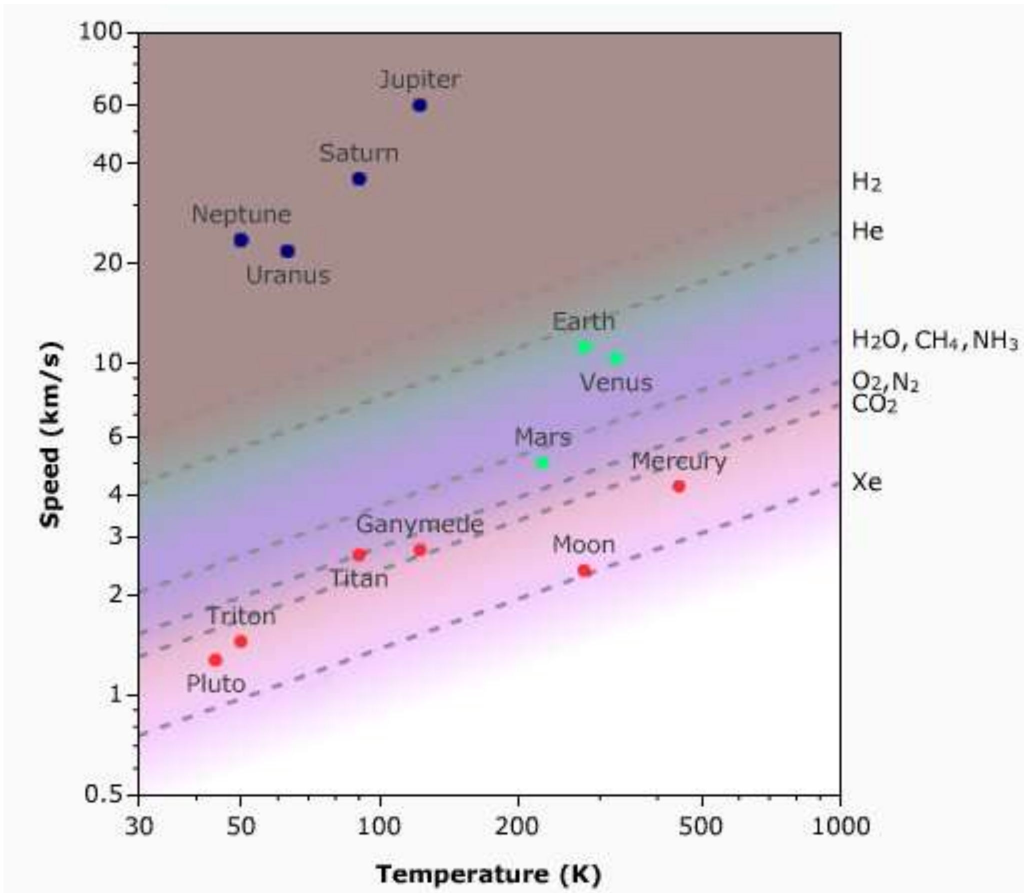


Figure 15. *Escape velocity of gas vs. atmospheric temperature for each planet.* From http://m.teachastronomy.com/astropediaimages/gasretention.jpg

The Earth's atmosphere serves as a biological "skin", shielding life against deadly solar radiation in the ultraviolet and X-ray regions of the spectrum and the impact of an estimated 300 tons of small bits of space debris that strike the Earth daily.

The atmosphere of the Earth hugs the surface in a thin layer, with 99% of the atmosphere found within 32 km of the surface. The atmosphere is by mass 78% nitrogen and 21% oxygen with traces of water vapor, hydrogen, carbon dioxide, methane, and **nitrous oxide.**

B. Evolution of the Earth's Atmosphere

The Earth's atmospheric composition has gone through three phases of evolution. Earth's primitive atmosphere was constituted mainly of hydrogen and helium, the main constituents of the Sun and gas giant planets. These are the lightest gases and were soon lost to space, having exceeded the Earth's escape velocity.

Earth's second atmosphere was composed of carbon dioxide and water vapor, emanating from the Earth's interior. Today volcanoes emit gas composed, on average, of 58% water and 24% carbon dioxide by weight. Most of the water went into the formation of the Earth's oceans. Carbon dioxide was removed from the atmosphere by dissolving in the oceans. Carbon dioxide in ocean water is then used by marine life to produce shells, which are made of calcium carbonate. In turn, shells from dead marine life accumulate on the bottom of the ocean forming sediment, which is eventually compressed into carbonate rock. When life formed on land, it also removed carbon dioxide from the atmosphere, converting it to oxygen and organic nutrients. This conversion of carbon dioxide takes place today in plants undergoing **photosynthesis**.

Removal of carbon dioxide from the atmosphere and oceans led to our current atmosphere, which is 3 parts nitrogen and 1 part oxygen, about 2.5 billion years ago. Evidence for this change include **sedimentary rocks** which underwent a chemical change from oxygen-poor to oxygen-rich about 2.5 billion years ago, as well as the existence of fossil algae from 2.5 billion years ago that are now found only in oxygen-poor environs. An oxygen-rich atmosphere is evidence that a planet is capable of supporting life as we know it.

C. Oceans

Earth is the only water-covered planet, and only one of two solar system bodies possessing oceans (the other is Europa, a moon of Jupiter). Seventy-one percent of the Earth's surface is covered by water. Ninety-seven percent this water is contained in the Earth's oceans; three percent is found on the continents. Seventy-seven percent of the water found on the continents is tied up in water ice on the polar caps.

Circulation of water in the oceans occurs in much the same way as atmospheric circulation, by the warmth of the Sun and rotation of the Earth. Temperature differences between water at the Equator and Poles in combination with coriolis causes global clockwise and counterclockwise ocean circulation patterns (Figure 4).

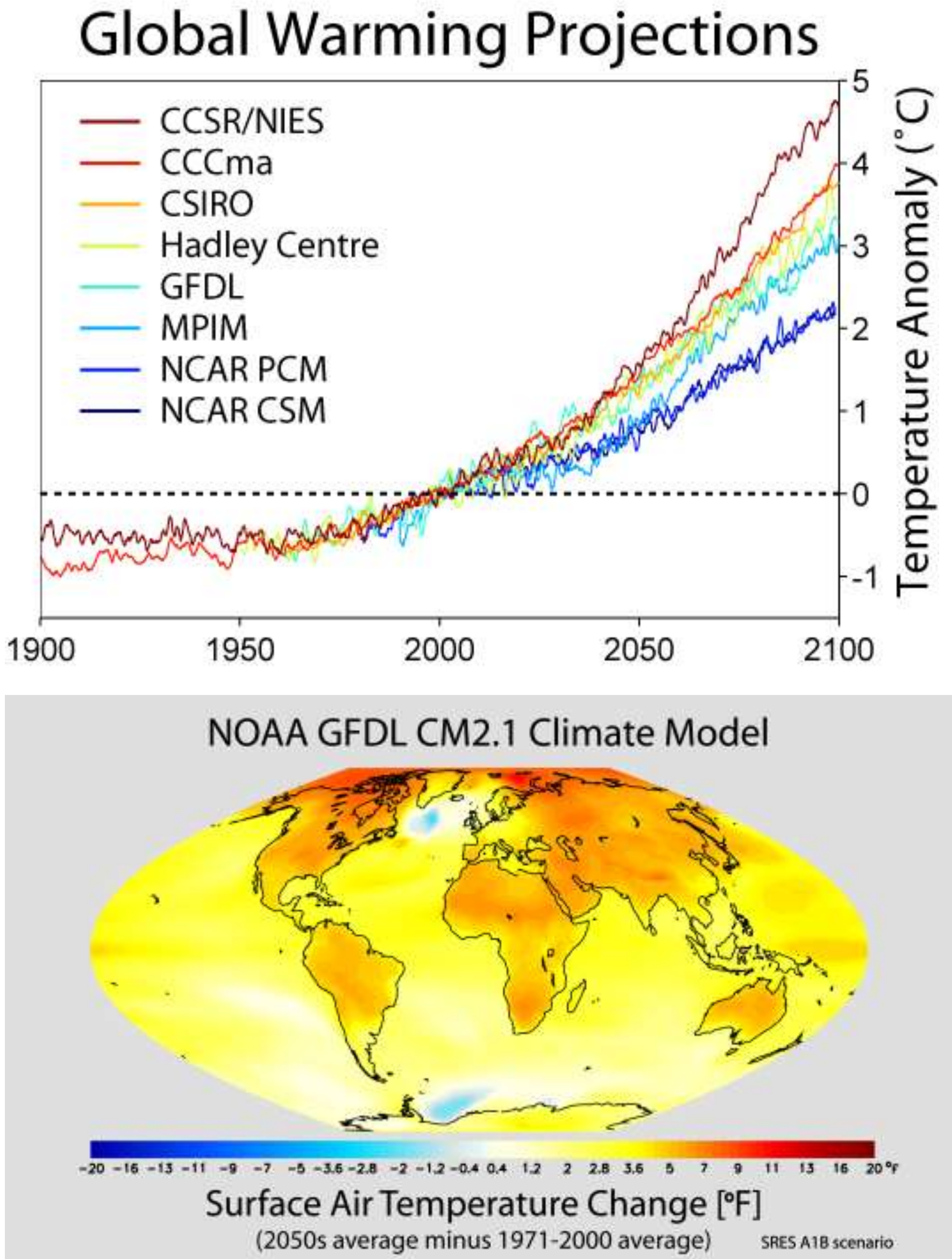


Figure 16. ***Panel A.*** *Projections of global warming from 8 different models.* ***Panel B.*** *Increase in air temperature in 1950 based on a NOAA model. From http://en.wikipedia.org/wiki/Global_warming*

VIII. **Climate and Climate Change**

The Earth's **ecosphere** is a thin life-supporting envelope about 10 kilometers thick covering the globe. The interplay between land, oceans, and atmosphere is a complex and fragile one, which humans are only beginning to understand. We do know that the other eight planets in our solar system have evolved in such a way that they are apparently barren, incapable of supporting life because of temperatures that are too hot or too cold, absence of life-giving water or atmosphere, and too little protection from the harmful rays of the Sun and the constant bombardment of space debris. It is only prudent that scientists are wary of the possible harmful modifications to Earth's environment by discharging of harmful gases into the atmosphere, disposal of waste in the oceans, and the clear-cutting of forests. Such actions can have unintended and long-term effects on the life-supporting capability of the ecosphere. Two of the major problems effecting the long-term health of the ecosphere are the possible destruction of the Earth's ozone layer and the **greenhouse warming** of the Earth as a result of carbon dioxide pollution.

Ozone molecules, O_3, in a **stratospheric** layer which if at the Earth's surface would be compressed to a few millimeters in thickness, protects the Earth surface from the Sun's ultraviolet radiation. Ultraviolet light is energetic enough to damage organic molecules. The ultraviolet light that does penetrate the atmosphere causes skin tanning and skin cancer. Chlorofluorocarbons, a gas previously used in refrigerators and air conditioners, released into the atmosphere by humans have broken down significant amounts of ozone in the upper atmosphere, the **stratosphere.** This is similar to chemical processes observed in the atmospheres of Venus and Mars.

Venus, Earth's twin planet because of its similar size, heavy atmosphere, and distance to the Sun, is a hellish environment. Its heavy carbon dioxide atmosphere acts as a one-way window to sunlight (Figure 17). Visible sunlight penetrates the upper atmosphere warming the surface and lower atmosphere. On an airless planet, the surface temperature would be moderated by reradiation of infrared radiation from the planets warm surface into space. But the heavy carbon dioxide atmosphere acts like glass in a greenhouse or a car with its windows rolled up on a sunny day. Visible light penetrates carbon dioxide like it does clear glass; but infrared rays from the warm surface are blocked by carbon dioxide and glass alike. While a car on the Earth becomes stiflingly hot, the Venusian atmosphere has become a blazing inferno, at 900° F it is hot enough to melt tin and lead. Is this a view of what could happen on Earth if enough carbon dioxide were dumped into the atmosphere from automobile exhaust, power plants, and factories? It is unlikely that the Earth's surface will reach 900° F anytime soon, but the possible effects are serious.

WebVideo: the Greenhouse Effect
http://www.youtube.com/watch?v=Kr02VF3ralc
http://www.youtube.com/watch?v=kKVqEnFVSCU
http://www.youtube.com/watch?v=52KLGqDSAjo
http://www.youtube.com/watch?v=oJAbATJCugs

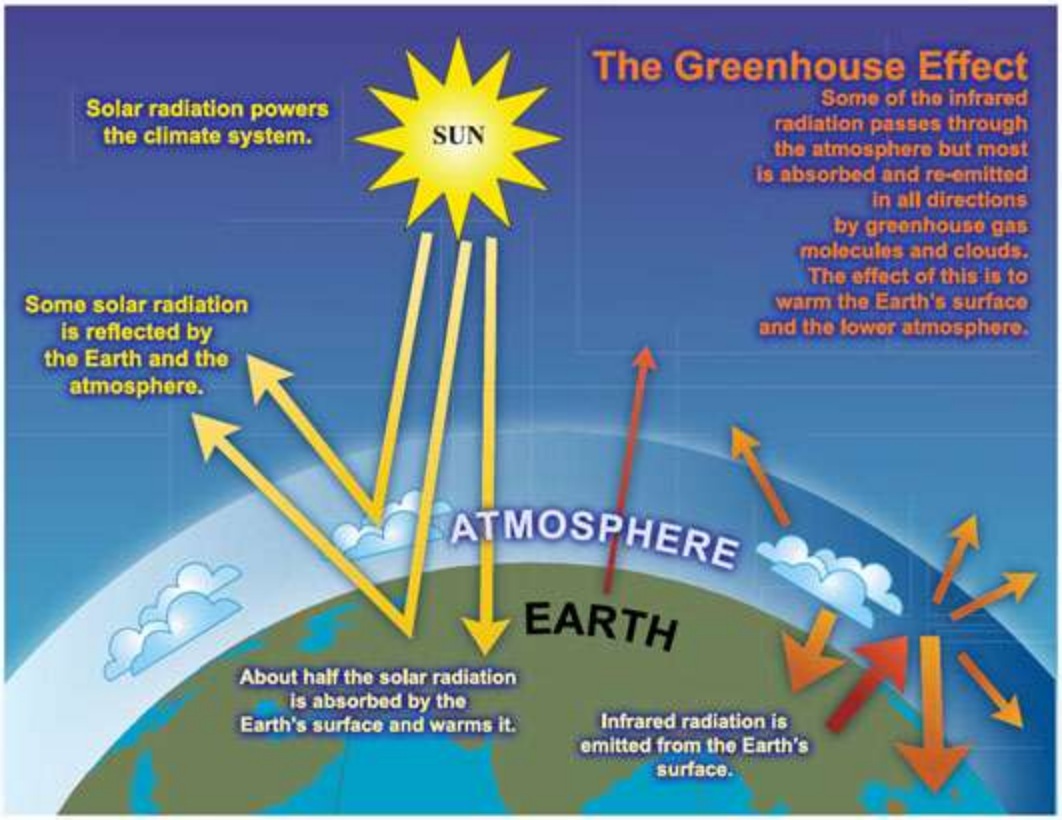


Figure 17. *The greenhouse effect from the Earth's atmosphere. The visible portion of the Earth's spectrum penetrates the cloudless part of the atmosphere and warms the surface of the Earth. The Earth's surface re-radiates this energy in the infrared part of the electromagnetic spectrum. Infrared radiation is absorbed by carbon dioxide and water in the Earth's atmosphere, which blanket the Earth's surface and keep its temperature higher than it would be without an atmosphere. From* www.global-greenhouse-warming.com

Water vapor and carbon dioxide both exhibit greenhouse properties; they are transparent to visible light and opaque to infrared rays. To compound any change in climate due to increasing carbon dioxide and water vapor levels in the atmosphere, these level naturally increase with increasing temperature. Increasing greenhouses gases could cause a runaway effect – more carbon dioxide results in higher temperatures, resulting in even more carbon dioxide, etc.

It is believed that increasing levels of carbon dioxide worldwide due to global industrialization will cause a continued warming of global climates well into the 21st century (see www.). How much warming is serious? A global temperature drop of only 5° K caused the great ice age, which covered most of North America with a sheet of ice. An increase in 2 K would convert significant acreage of fertile land to desert at low-latitudes, shifting agriculture to more northerly latitudes. Melting of the polar ice caps would raise ocean levels, inundating low-lying coastal lands, where most of the world's population lives. A taste of the social and political problems can already be seen in places like Somalia where desertification of once-fertile lands has produced starvation and political unrest.

Summary

In order to understand the planets in our Solar System we must first understand the properties of the Earth as a whole. The Earth is the only body in the Solar System with oceans, solid surface, and a substantial atmosphere. It has a surface that is heavily eroded and geologically active. The Earth's weather and ocean circulation is influenced greatly by its rotation, which produces the coriolis effect. The age of the Earth has been determined by radioactive dating of terrestrial rocks to be older than 3.9 billion years old. Dating of other more unaltered bodies in the Solar System indicates that the Earth probably formed about 4.6 billion years ago. The Earth is heated on the inside from radioactive decay of unstable isotopes. This heat keeps a large fraction of the Earth's interior molten. This heating has caused the denser materials in the Earth to sink to its center, producing a nickel-iron core and also allows the continents to float and drift on a flowing layer of rock in the Earth's mantle. The motion of the Earth's fluid interior produces an electric current that gives the Earth a magnetic field. The Earth's atmosphere has and is continuing to undergo dramatic change. The Earth has evolved from a primitive hydrogen/helium atmosphere, which subsequently evaporated, to a carbon dioxide atmosphere produced by volcanic outgassing. The latter disappeared when carbon dioxide dissolved into the Earth's oceans, producing carbonate rocks. The result is our current oxygen- and nitrogen-rich atmosphere. Now industrial pollution threatens to heat our atmosphere through the greenhouse effect.

Key Words & Phrases

1. **Aesthenosphere** - a deformable or plastic layer of rock underneath the Earth's lithosphere. From the Greek for "weak rock".
2. **Aurora –** intense atmospheric emission that occurs during periods of intense solar activity, when solar wind collide with gas molecules in the upper atmosphere causing gas molecules to emit light.
3. **Continental drift -** the motion of the Earth's continents in which they collide and separated, sliding across the Earth over hundreds of millions of years
4. **Convection –** the transport of heat by the motion of packets of fluid
5. **Coriolis** – the phenomenon in which a spinning planet causes the deflection of moving objects on its surface, including masses of air or water. On the Earth, coriolis causes cyclonic wind circulation patterns in the Northern Hemisphere.
6. **Daughter nucleus -** a nucleus that is a product of a radioactive decay is called the daughter nucleus
7. **Differentiation -** gravitational separation of materials in a planet according to their density
8. **Ecosphere -** the layers in the Earth's crust and atmosphere in which life is found

9. **Field** – the spatial variation of a parameter throughout a volume. One example is the magnetic field is the variation of magnetic force throughout a volume of space.
10. **Greenhouse effect –** the phenomenon whereby a planet traps the energy from solar illumination with atmospheric gases such as carbon dioxide.
11. **Isotope -** nuclei with the same number of protons but a different number of neutrons are called **isotopes** of the same element.
12. **Lithosphere - t**he outer, cool part of the Earth's crust and upper mantle that is made of relatively rigid, brittle rock. Lithosphere is from the Greek for "rock sphere".
13. **Magnetic force** - the force generated by moving charge, e.g. an electric current in a wire
14. **Oblate spheroid** – a flattened spherical shape
15. **Parent nucleus -** the original nucleus prior to its decay into a nucleus of a different type is called the parent nucleus
16. **Photosynthesis -** the process used by plants to generate the chemical energy that they require from incident sunlight
17. **Plate tectonics -** a theory of the motion of continents over the Earth's surface
18. **Sedimentary rocks**
19. **Solar wind -** high-energy particles boiled off the Sun's atmosphere, including protons and electrons, which continuously impact the Earth
20. **Stratosphere –** the portion of the Earth's atmosphere above the troposphere (where temperature decreases with altitude) to about an altitude of 30 miles above the Earth's surface.

Review for Understanding

1. What is the age of the Earth? How has it been determined?
2. Explain, using a diagram, coriolis.
3. Using a diagram, explain plate tectonics and show how it is involved in building landforms on Earth.
4. List as many methods as you can for probing the internal properties of the Earth.
5. Using a diagram illustrate and define the upper layers of the Earth's interior: the crust, mantle, solid core, liquid core, lithosphere, and aesthenosphere.
6. Explain how the Earth's greenhouse effect could become a runaway phenomenon.
7. Describe in your own words a field. Use an example other than the Earth's magnetic field.

Essay Questions

1. Describe how differentiation has occurred on the Earth. How has this affected the Earth's internal structure? Its appearance?
2. How does the Earth's rotation affect its weather?
3. What effects do automobile and industrial pollution have on the Earth's mean temperature? Explain.

4. You have a one-gram sample of pure radioactive Argon-30, which decays to Argon-30 with a half-life of 260 years. How much Argon-30 will you have 260 years from now? 520 years from now? 780 years from now?
5. Describe how you would expect the Earth's magnetic field to change over the next 1 billion years.

Chapter 8 - The Moon: Our Sister Planet

How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth?
Sherlock Holmes in "The Sign of Four" by Sir Arthur Conan Doyle, 1890

Chapter Preview

As much as the Earth is key to our understanding of the processes at work in the Solar System today, the Moon is key to our understanding of the processes at work in our Solar System in the past, from its origin 4.6 billion years ago through a period of intense bombardment from objects up to 10s of kilometers in diameter which blasted the craters that distinguish the Moon's surface today. Why does the surface of the Moon appear so different from that of the Earth? How did the Moon form? What clues can we gather about the origin and evolution of the Solar System as a whole? These are some of the most important questions that scientists continue to attempt to answer today and which you will study in this chapter.

Chapter Photo. *Neil Armstrong, the first man to step onto the Moon, 1969. (NASA)*

Key Physical Concepts to Understand: *differences in the Earth and Moon, differences between the Moon's maria and highlands, origin and evolution of the Moon, cratering of the Moon's surface, origin and effects of tides between Earth and Moon, the effect of the absence of an atmosphere on the Moon's surface*

I. Introduction

The Moon is one-quarter the diameter of the Earth, larger with respect to its parent planet that the moon of any other planet (Figure 1). (It is conventional to capitalize the natural satellite of the Earth and refer to the natural satellite of any other planet as a "moon.") At about the same size as Mercury, the Moon could correctly be regarded as the sister planet of the Earth, and the Earth-Moon system as a binary (or double) planet system. But why are these siblings so different? The Earth has a substantial atmosphere covering a surface that is one-quarter land and three-quarters ocean. Life is abundant here. Landforms are complex and varied, and include volcanic mountains, folded mountains, river valleys, dune-covered deserts, and glacial moraines. The Moon appears stark and lifeless. It has no significant atmosphere, no visible surface water, no ice caps, and no recent evidence of either volcanic activity or plate tectonics. Instead its gray and black surface is saturated by craters of impact origin and large expanses of lava plains. There is no evidence of life, past or present.

Figure 1. *Earth and Moon: a double planet. An image of the Earth and Moon, both at quarter phase, taken from the Voyager interplanetary spacecraft.* **NASA**

Why is there such a difference? As you will see, most planetary scientists believe that the Moon is similar to the primitive Earth billions of years in the past. Both went through an intense period of cratering. **The evolution of the Moon's surface has deviated from that of its bigger sister because of the Moon's size.** Its smaller surface gravity has allowed the molecules of its primitive atmosphere, including water, to exceed its gravitational escape velocity and simply boil off the surface. Lack of an atmosphere has left the Moon with a pristine surface, unaltered by erosion from wind, water, and ice and chemical interaction with a corrosive, oxidizing atmosphere, all of which have contributed to the constant destruction and alteration of the Earth's surface. Except for a few footprints left by visitors in the 20th century, the Moon's surface hasn't significantly changed in 3 billion years (Chapter Photo). This fact alone gives us inspiration to travel to the Moon to study its surface and bring back samples.

Table 8.1: *Lunar Sample Return Missions, Manned Apollo & Unmanned Luna*

Mission	Country	Year	Details
Apollo 11	US	1969	1st human landing on Moon, Mare Tranquillitatis
Apollo 12	US	1969	Oceanus Procellarum
Luna 16	USSR	1970	Unmanned, Mare Fecunditatis
Apollo 14	US	1971	Mare Nubium
Apollo 15	US	1971	1st lunar rover, Mare Imbrium/Hadley Rille
Luna 20	USSR	1972	Unmanned, Mare Fecunditatis
Apollo 16	US	1972	Descartes highlands
Apollo 17	US	1972	Taurus mountains
Luna 24	USSR	1976	unmanned, Mare Crisium

II. Gross Properties

The Moon has a diameter roughly one-quarter that of the Earth and approximately 1/6th the surface gravity. The result is that any of the atmosphere and water that formed on the Moon's primordial surface soon evaporated into space, along with any possibility for the formation of life. The Moon's visible, or near side, is covered by 30,000 craters that can be seen by telescopes. Such craters have diameters from 1 kilometer to 1200 kilometers. In contrast, the Earth's surface shows evidence of less than 200 ancient craters, the others having presumably been eradicated by the relentless forces of erosion and volcanic activity over billions of years.

The gray, cratered moonscape is broken only by smooth, dark lava flows extending over 100s of kilometers (Figure 2). These **maria** (mar-ee-uh), Latin for oceans, were named for their smooth, dark appearance, and not for any evidence of water. The maria are 2 to 5 kilometers below the average elevation and cover approximately 15% of the lunar surface. The heavily cratered surface is 4 to 6 kilometers above the average lunar surface and is called the lunar **highlands**. Bright linear **rays** extend outward from the larger craters, marking the surface where bright material from the subsurface was excavated by an impact crater and thrown across the darker surface of the Moon (Figures 3-6).

Figure 2. *Mare Imbrium is one of the lunar maria, which cover about 17% of the Moon's surface. In the background are the bright crater saturated lunar highlands and the 100-km crater Copernicus.* NASA, Apollo 17.

Figure 3. *Craters and rays. This contrast enhanced photograph of the full moon shows rays emanating from craters in sharp contrast. Rays are lines of small craters formed when clots of material are thrown from the impact that forms a larger crater. From www.apod.nasa.gov.*

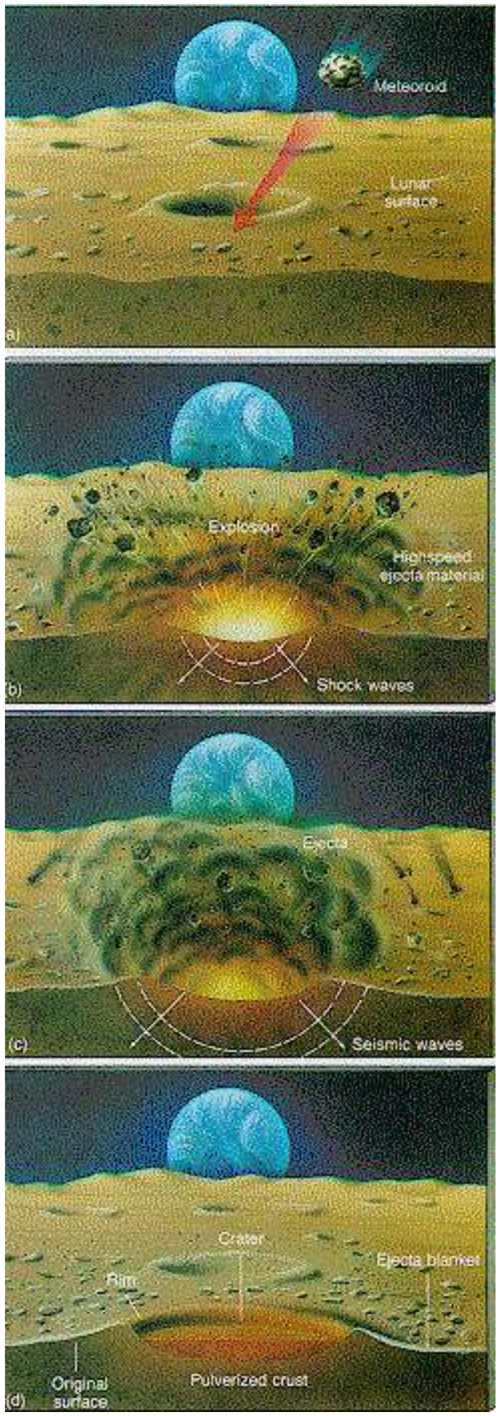


Figure 4. *Drawing of cratering event. This schematic illustrates phases in the formation of a crater. A meteoroid impacts the lunar surface. On impact the energy of motion of the meteoroid is converted into an explosion which produces shock waves and excavates surface material, ejecting it at high velocity. The result is a rimmed crater surrounded by a blanket of excavated material.*

Figure 5. *The full Moon. The heavily cratered highlands are the bright portions of the crust; the darker Maria are labeled. Also marked are the 6 American manned, Apollo landing sites and the 3 Soviet Luna, robot sample return landing sites.* **P 146-8.2.**

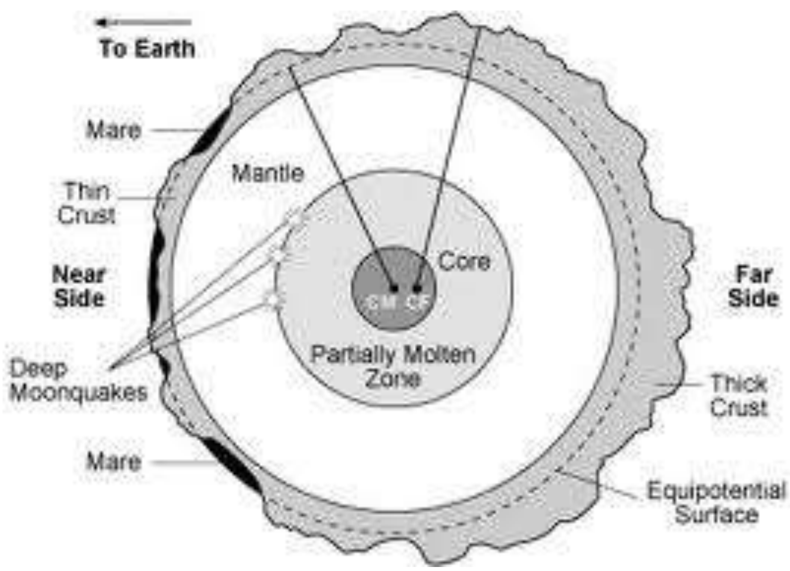


Figure 6. *The lunar interior. The crust is approximately 1000 km thick. At one time, tremendous impacts in the lunar crust excavated basins and produced fractures in the lunar surface allowing molten mantle material to seep to the surface, freshly paving the low-lying maria with dark basaltic lava. From ase.tufts.edu*

Table 8.2: *Bulk Properties of the Moon*

Property	Measurement
Mass	0.012 M_{Earth}
Radius	3476 km 0.272 R_{Earth}
Average Density	3340 kg/m^3
Average Distance from the Earth	384,600km (238,900 miles)
Orbital Period - Sidereal	27.3 days
Orbital Period - Synodic (1 cycle of phases)	29.5 days
Orbital Eccentricity	0.055
Sidereal Rotational Period	27.3 days

III. Interior of the Moon

The bulk density of the Moon is 3300 kg/m^3 as compared with 5500 kg/m^3 for the Earth and 2700 to 3300 kg/m^3 for the Earth's continents and ocean floors, respectively. This suggests that the Moon lacks a large iron core like the Earth's. (Iron has a density of approximately 8000 kg/m^3, so a large core would increase the Moon's bulk density well above the density for crustal rocks.) However, metallic rocks on the Moon have been magnetized and indicate a historical lunar magnetic field with about 4% of the strength of the Earth's present magnetic field. This is evidence of a small, perhaps completely solid iron lunar core.

Only the Moon and Mars have had seismographs planted on their surface. Major moonquakes are generally mild compared to earthquakes and occur at depths of 700 to 1200 kilometers. On Earth, quakes occur in the rigid lithosphere, as a result of a shifting and cracking crust, at a depth of 50 to 60 kilometers. This indicates that the Moon has a thick crust extending to a depth of 1000 kilometers. This is a result of a Moon that has cooled more rapidly than the Earth due to its small size. There is no evidence of current volcanic activity or faulting at tectonic (continental) boundaries. Moonquakes are 0.5 to 2 on the Richter Scale, compared to 5-8 for major earthquakes on Earth, indicating a relatively inactive planet, geologically. On Earth, quakes occur in the rigid lithosphere where plates collide or descend into the aesthenosphere. Planetary geologists interpret the lunar quake data as indicating a crust to 40-60 km depth, a solid mantle to a depth of 900-1000 km, and a small core, perhaps 400 km in diameter (Figure 6). It is not settled whether this core is solid or liquid.

Radar images of the moon penetrate the Moon's surface and give us an idea of the porosity of the lunar surface, whether it is covered by porous soil or solid rock. Such images show that the Moon's highlands are less dense than the maria. The maria are basins that have been filled in with flows of dark lava. Spacecraft orbiting the Moon provide additional evidence. By tracking spacecraft it is possible to determine any slight deviations from a purely elliptical orbit, as would be predicted by simple theory. Such deviations show that certain regions of the lunar surface attract spacecraft significantly more strongly than other areas; these regions are called mascons, from "mass concentration". Mascons found to coincide with the maria, which would be consistent with the material in the lava flows having a higher mass density than surrounding material.

The far side of the Moon (not the dark side) is rather uniformly cratered, containing only one mare region, probably a result the lunar crust being somewhat thicker on the near side than the far side (Figure 7).

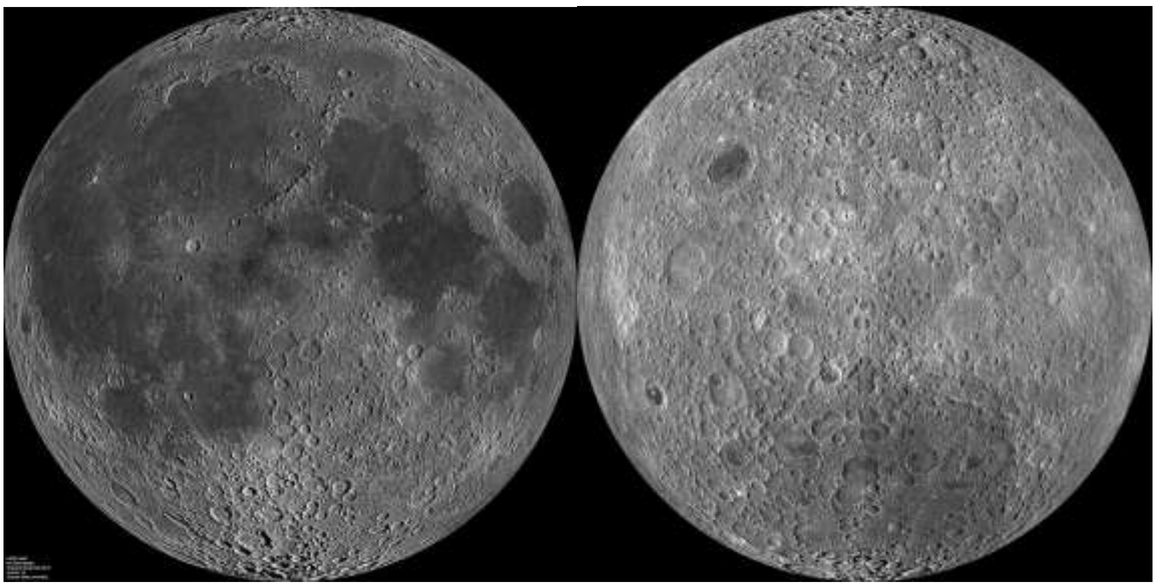


Figure 7. Near (left) and *Far (right) side of Moon. The near side of the Moon has a thinner crust; as a result impact cratering penetrated the crust on the near side resulting in volcanic plains, or maria. The far side is devoid of large maria. (NASA)*

IV. Surface of the Moon

The surface of the Moon was thought to be perfectly polished (remember, all of the planets were presumed to be perfect celestial objects by the Aristotelians) until Galileo and Englishman Thomas Harriot first viewed the Moon by telescope in 1608. They saw rugged mountains and irregular valleys.

The first spacecraft to land on the lunar surface showed that it was covered by a fine powdery soil or regolith 1 to 30 meters deep everywhere. Lunar soil is unlike terrestrial soils in that it contains no organic materials.

Most knowledge of lunar composition is based on 382 kilograms of lunar regolith and rock samples returned to Earth by the U.S. Apollo landers and the Soviet Luna landers. Rocks generally fall into three categories: **basalt**, **anorthosite**, and **breccia** (Figure 8).

Basalts are the darker and denser silicates formed from cooling lava in the lunar maria and are also found in lava flows on Earth. The lunar highlands are covered with anorthosites, a less dense and brighter silicate similar to the rocks composing some of the oldest mountain ranges on Earth, such as the Adirondacks. The third type of rock is actually a combination of the first two. Breccias are rocks formed from individual, heterogeneous rock fragments welded together to form single rocks by meteorite impacts. Meteorites of all sizes have impacted the surface of the Moon over a period of billions of years. This has accomplished two things. First the original rocky crust has been fragmented and shattered into a regolith many meters deep, blanketing the entire lunar surface. Second, meteorite impacts reconsolidate this regolith by building breccia, releasing enough impact energy into the soil to heat weld regolith fragments into rock.

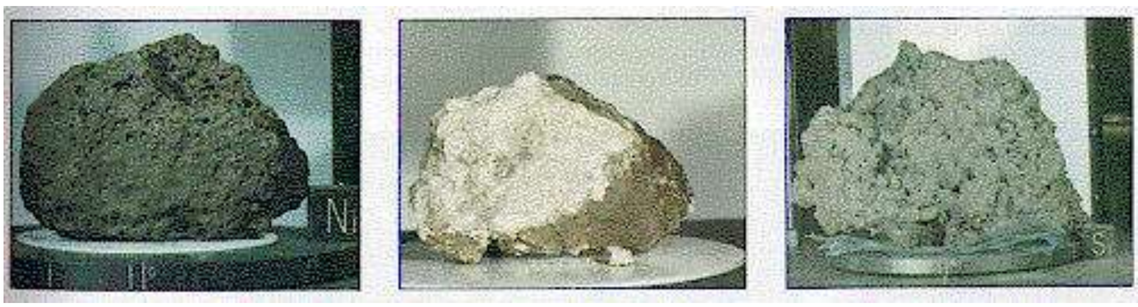


Figure 8. *The three major types of moon rocks.* **Panel A.** *A dark mare basalt. A 1-cm block is shown for scale.* **Panel B**. *A highlands anorthosite.* **Panel C.** *A gray and white breccia.* **P 149-8.8&8.9&8.10.**

The oldest rocks or rock fragments found in the lunar sample return collection are individual breccia fragments that have been radioactively dated as solidifying about 4.6 billion years ago (Figure 9). The vast majority of lunar rock samples are dated between 3.0 and 4.2 billion years of age. This indicates that although the Moon formed about 4.6 billion years ago, the surface was continuous state of intense surface modification from 4.6 billion to 4.2 billion years ago, and has undergone almost no modification over the last 3 billion years. The lunar surface is now much the same as it was 3 billion years ago, with the exception of light gardening by relatively small meteorites and the darkening of the lunar soil made by exposure to the solar wind. Samples returned by six manned U.S. and three robotic Soviet lunar landers have provided us unique and valuable evidence of the state of the solar system 3 billion years ago. It can be argued that in the 382 kg of returned lunar samples, scientists have more direct evidence on the state of the primitive Moon than they have from all of the evidence that has been collected from geological samples of our own planet. Evidence for the formation of the lunar surface comes from radioactive dating, compositional analysis, and studies of the physical state and mineralogy of returned rocks and regolith samples. By combining radioactive dating with physical, chemical, and **mineralogical** analysis, a reconstruction of the history of the Moon can be made.

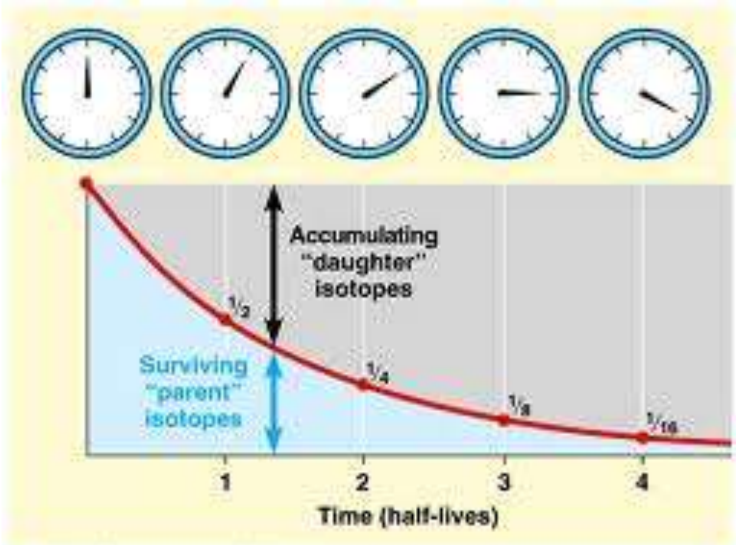


Figure 9. *Radioactive dating. From* *www.kirkgivens85.edublogs.org*

In 1995 scientists used radar aboard the Clementine satellite to determine that the south polar region of the Moon is highly reflective (Figure 10). Polar areas are deeply shadowed and therefore extremely cold. It is presumed that the highly reflective polar cap is indicative of a water ice cap. Even though the daytime surface of the Moon can be extremely hot, the north polar cap is cold enough to support the existence of water ice. The existence of water is extremely important for the establishment of a lunar base. Not only would water be important for its own sake, but could be used to produce oxygen for space travelers.

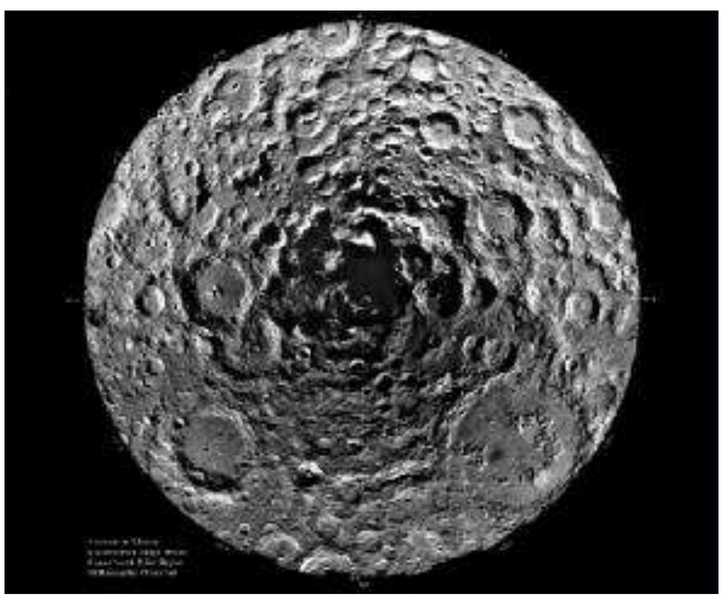


Figure 10. *The South Pole of the Moon imaged by the Clementine spacecraft. The dark crater at the center of the disk is the South Pole-Aitken impact basin, the largest known crater in the Solar System. This deep crater is in permanent shadow. Recent radar data indicate that the bottom of this crater contains solid ice, perhaps brought to the moon by comet impacts. (NASA)*

V. Dating the Moon's Surface

The surface of the Moon is not uniformly cratered; the density of craters varies widely from place to place, with the most dramatic difference between the relatively smooth craterless maria and the nearly crater-saturated highlands. If we assume a relatively straight-forward model of lunar cratering, with the number and size of meteorites impacting the Moon's surface relatively constant in time, then it is easy to see how the number density of craters on the Moon's surface would vary with the age of the surface (Figure 11). Recent lava flows, if any exist, would be devoid of craters not having been exposed to impacts for a significant period of time. The most ancient of the lunar terrain would be expected to possess the highest density of craters. Indeed, planetary scientists use this technique of counting the number of craters per square kilometer to assign relative ages to regions of the Moon's surface. By radioactively dating samples returned from different regions of the Moon the technique has been confirmed and calibrated.

WebVideo: Lunar Chronology http://www.youtube.com/watch?v=UIKmSQqp8wY

Figure 11. *Dating of the Moon's surface. These images represent four areas of lunar surface of widely differing age/cratering density. The upper left represents the youngest surface and the lower right the oldest. (NASA)*

VI. Evolution of the Moon

Comparing the crater density of the areas of the Moon that have been radioactively dated, it has been determined that the lunar cratering rate has not been uniform, as was assumed once, but has undergone an episode of intense cratering, immediately after the Moon's crust originally solidified, steadily decreasing with time. It is assumed that the Earth's surface suffered the same impact rate, but evidence has literally been eroded with passing time, from water, wind, and ice, and the repaving of the Earth via plate tectonics.

4.6 billion years ago: solidification of the lunar crust. The oldest breccia fragments found in the returned lunar samples indicate that the Moon was formed some 4.6 billion years ago (Figure 12). Cratering subsequent to the formation of the Moon indicates that the Moon formed by the gravitational accumulation of large meteorites or **planetesimals**. As these objects bombarded the surface of the primeval Moon they released enough energy on impact to keep the surface of the Moon molten. As intense cratering lessened the lunar surface solidified.

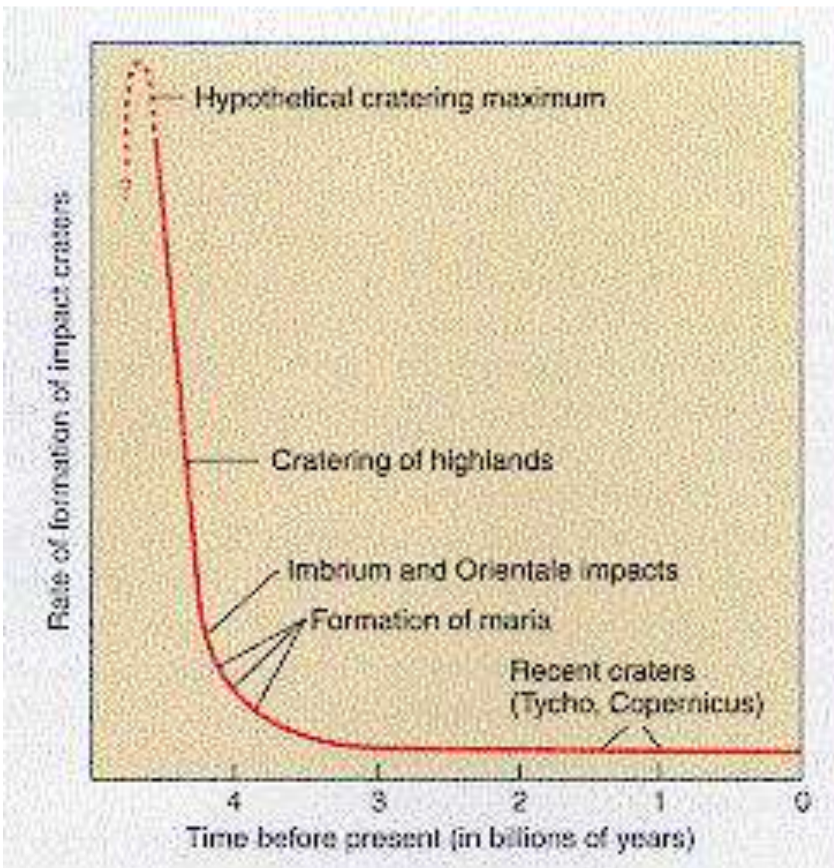


Figure 12. *Time line of lunar evolution.*

4.6-3.6 billion years ago: intense general cratering and maria formation. After the initial accumulation of planetesimals in the solar system some 4.6 billion years ago, there followed a period of general cratering for another one billion years. During this period of time the Moon appears to have swept up material in its immediate neighborhood that remained after its formation. The largest meteorite impacts excavated the enormous basins on the surface of the Moon that correspond to the maria (and associated mascons) that we see today. The radioactive isotopes accumulated into the interior of the Moon slowly released energy, which served to remelt the lunar interior. Molten basaltic lavas then poured onto the lunar surface through fractures in the basins, and filled these low lying areas with dark, dense rock over a time interval of several million years. As a result these maria are less cratered (younger), darker, and denser than the surrounding highlands.

3.6 billion years to the present. Little lunar geological activity has occurred over the last 3.6 billion years. Because of its small size, the Moon has cooled rapidly, forming a thick (1000 km) lithosphere, with no significant tectonic plate fractures. Most, if not all, of the Moon's core has solidified resulting in only a small fossil remnant of its original magnetic field (generated by a conductive liquid in motion). Only a light rain of micrometeorites has altered the lunar surface until now, tilling and deepening the lunar regolith.

VII. Origin of the Moon

The Earth-Moon double planet system is unique in our Solar System. Attempts to explain its origin are made difficult by the systematic differences in composition between the Moon and Earth. These differences must be explained in order for any theory of the origin of the Moon to be considered adequate. The abundances of elements and their isotopes are different between the Earth and Moon **(Table 8.3).** Overall the isotopic and elemental abundances are similar, but the Moon has a greater abundance of the elements that can solidify at high temperatures (such as aluminum and titanium), called **refractories,** and a lesser abundance of elements and molecules that can only solidify at cool temperatures (such as water and oxygen), called **volatiles**. The Moon is less differentiated than the Earth, so it has a more homogeneous distribution of elements. (One example is iron; iron is distributed throughout the lunar interior, and is found in abundance even in the crust. This would partially explain the apparently small lunar iron core.) A third difference is the abundance of iron. Although in abundance in the lunar crust, it is significantly lower in abundance than in the crust of the Earth. Of the four theories outlined below, the last and most modern theory is the only one that explains the differences in bulk composition between the Moon and Earth.

Table 8.3: *Evidence Relating to Theories of Lunar Formation*

Evidence Bearing on Theories of Lunar Formation
1. The abundance of iron in the lunar crust is much less than in the Earth's crust.
2. There is almost no water or other volatiles in the lunar crust, but there are in the Earth's crust.
3. The ratio of abundances of oxygen isotopes is the same in the Moon and Earth, but varies strongly with heliocentric distance from planet to planet in the solar system.

Capture Theory: the Moon was formed far from the Earth and was later captured by the Earth. Pros: This theory is supported by the differences in composition between the Earth and Moon. Since the Moon is depleted in volatiles relative to the Earth, it could be inferred that the Moon formed closer to the Sun than the Earth and was then captured by the Earth. **Cons:** No realistic mechanism has been proposed that would successfully explain how the Earth could capture a sister planet as large as the Moon.

Daughter Theory: the Moon was "torn" from the Earth, leaving a great depression, the Pacific Ocean. Pros: The differences in bulk composition between Earth and Moon can be explained as resulting from the difference between the bulk composition of the Earth and the Earth's crust. The Moon has a mean density and composition close to that of the Earth's crust. **Cons:** No one has successfully been able to model the separation of the Moon from the Earth. This theory would not explain why the Moon is depleted in volatiles. As a result of plate tectonics, the Pacific Ocean has not always had its present form.

Sister Theory: the Moon formed out of the same nebula of gas and dust at the same time as did the Sun, Earth, and the other planets. Pros: This scenario successfully explains why the Moon is in a nearly circular orbit about the Earth's equator: the Moon and Earth condensed out of the same cloud of preplanetary material. **Cons:** The bulk compositions of the Earth and Moon should be nearly identical under this theory and they are not.

Impact Theory: an asteroid slammed into the Earth, formed a ring of debris close to the Earth, out of which the Moon condensed. Pros: If the impacting object excavated material near the Earth's surface, and not the iron-rich core material, the result would be a Moon nearly devoid of iron. The heat of impact would have driven off water and other volatile molecules. The Moon would have condensed out of mantle material combined with the material making up the impacting asteroid, without the original volatiles. If the asteroid was a planetesimal formed at the same heliocentric distance as the Earth, the Earth's mantle, the asteroid, and the resulting Moon would all have roughly the same relative isotopic abundances of oxygen. **Cons:** There are no major difficulties with this theory.

IIX. Tides

One of the most interesting phenomena commonly associated with the Moon is tides (Figure 13). **Tides** are a raising and lowering of the Earth's oceans, and even the Earth's solid surface, caused by the difference in Moon's gravitational force between the side of the Earth nearest the Moon and the side farthest from the Moon. Tides tend to stretch the Earth apart like some gargantuan cosmic tug of war (Figure 14).

Figure 13. *High and low tide in the Bay of Fundy, Nova Scotia.* *From* www.amusingplanet.com

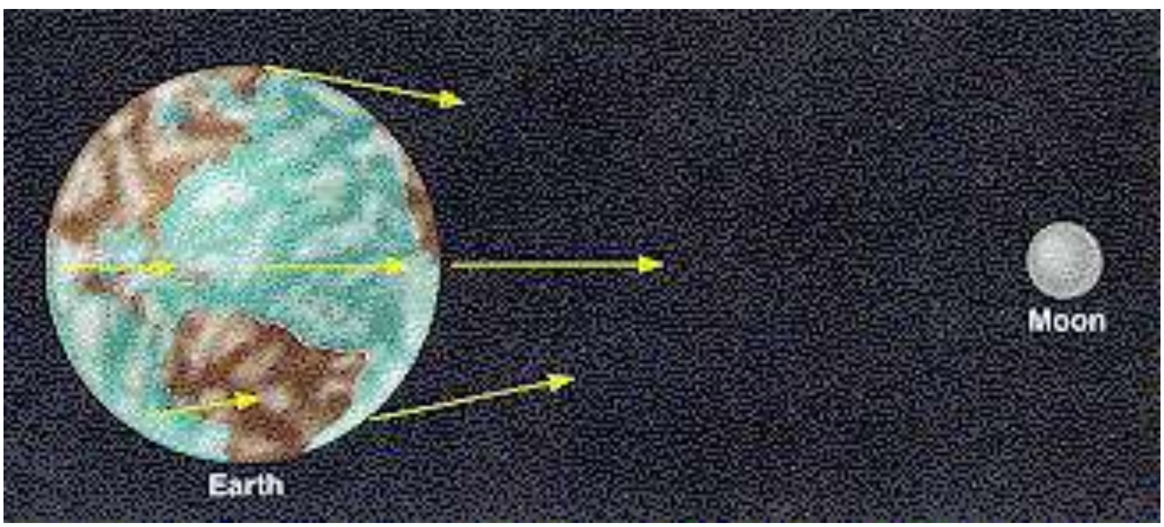


Figure 14. *The difference in the Moon's gravitational force between the Earth's near side and the Earth's far side produce tidal bulges in the oceans and continents***.** **FMW 73-3.15** altered to show ocean bulge.

Doesn't the force of gravity acting on the Earth from the Moon's mass simply pull the two planets toward each other? How could it possibly act to pull the Earth apart? Imagine two cars traveling down the highway; car A is towing car B with a nylon towrope. Nylon towropes are somewhat elastic and will stretch a little, like a thick rubber band, if pulled with sufficient force. Suppose the driver of car A is having difficulty keeping a constant speed. Initially both cars are traveling at 60 mph, but car A starts to pull away at a slightly higher speed, 65 mph. Although both cars are traveling in the same direction, car A is now slowly pulling away from car B (at 5 mph, the difference in speed between the two cars). As it does so the rope stretches, even though the two cars are moving in the same direction. An analogous phenomenon takes place as the Moon's gravity acts on the Earth and its oceans. The Moon is pulling on the entire volume of the Earth, but it pulls more vigorously on the Earth's near side than the Earth's far side, because gravity is an inverse square force and is stronger the closer two masses are. Like the two cars separated by the towrope, the two sides of the Earth are pulled apart by the gravitational forces of the Moon on the Earth's near side and far side, both acting in the same direction but with a difference in magnitude. This stretching pulls two bulges in the Earth's oceans, one toward the Moon on the Earth's near side and one away from the Moon on the Earth's far side. The size of these bulges is effected by the depth of water and local topography, but is typically many feet in elevation. A smaller bulge is also induced in the land mass of the Earth, but because water flows easily but land is rigid, this land or body tide is only a few millimeters in elevation. Although the Moon has no oceans, the Earth produces a body tide in the surface of the Moon.

Although the two tidal bulges in the Earth and its oceans are pointed toward and away from the Moon, the Earth surface is rotating once each 24-hour period. As a result, these two tidal bulges appear to slide across the surface of the Earth, producing two high tides and two low tides each day.

Webnote: Tides http://www.youtube.com/watch?v=gftT3wHJGtg

In addition to lunar tides the Sun also produces tides on the Earth. Even though the Sun is much more massive than the Moon, tidal effects vary dramatically with distance between masses; the Moon has a much larger tidal effect on the Earth than the Sun which is 400 times farther away from the Earth. When the Moon and Sun are either on the same side of the Earth or on opposite sides, stretch the Earth apart in cooperation, enhancing both high and low tides (Figure 15). These are called spring tides and occur at full and new Moon when the Moon and Sun are together in the sky or are opposite each other. When the Moon and Sun are at right angles to each other (at 1st or 3rd quarter moon) they act in competition, each pulling high tidal bulges in the low tide region of the other. The net effect is an attenuation of both low and high tides, called neap tides.

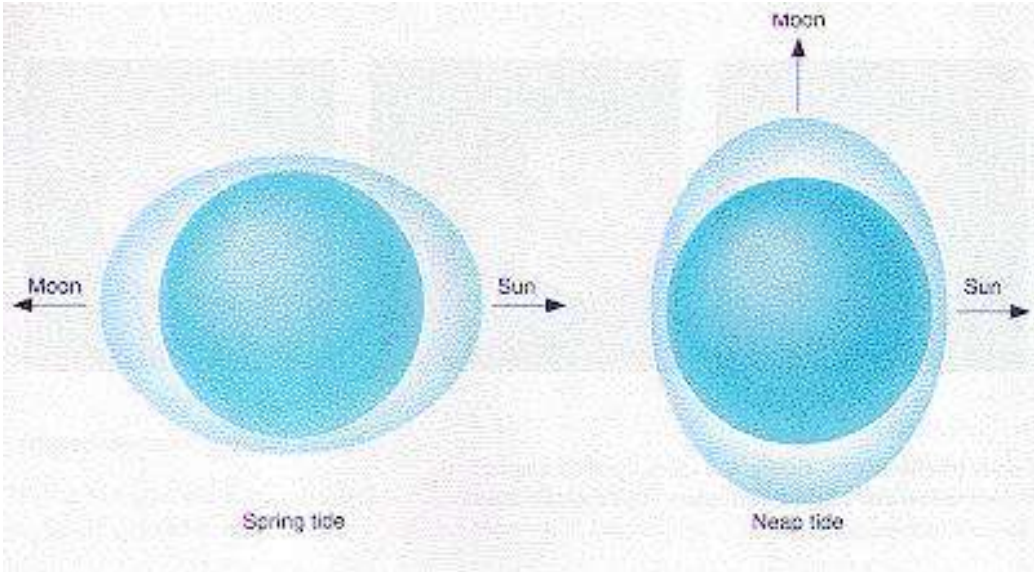


Figure 15. *The Earth's tides are dependent on the orientation between Earth, Moon, and Sun.* **Panel A.** *The strongest tides are spring tides, when the Moon and Sun are either on the same side of the Earth or opposite sides.* **Panel B.** *The weakest tides are neap tides; they occur when the Moon and Sun are separated by roughly 90° on the sky***.** **FMW 75-3.18.**

Note the difference between ocean tides and tidal waves. Tidal waves, more appropriately called tsunamis, actually have nothing to due with tides but are high intensity waves generated by earthquakes in the oceanic crust of the Earth.

The dragging of the tidal bulges across the Earth's surface dissipates energy through friction. This friction is slowing the rotation of the Earth and will continue to do so until the Earth no longer rotates with respect to its tidal bulges; at this point the Earth will rotate once every lunar month, keeping one bulge pointed toward the Moon and the other away from the Moon. This is called synchronous rotation. The Moon's rotation is already locked to it orbital period, so that it always presents the same side to the Earth, called the near side. Note that the near side is not the same as the dark side. In fact, during new Moon, the side of the Moon nearest the Earth is the dark side and the far side of the Moon is illuminated.

There is strong evidence that the Earth has slowed its rotation over millions of years. 500 million-year-old corals in the south Pacific exhibit daily and yearly growth layers, just as trees exhibit yearly growth rings. Five hundred million years ago there were 416 daily growth rings in a yearly band, manifesting 416 days in a year. This is evidence for a 21 hour day one half billion years ago, and a much shorter day before that time.

As the Earth and Moon have slowed in their rotation, some of this spin energy has gone into pushing the Moon away from the Earth into a larger and larger orbit. The Moon is moving away from Earth at roughly 4 cm/year, and may have started at one-tenth to one-half its present distance.

Summary

The Moon, although the Earth's nearest planetary neighbor provides a great deal of contrast with our own planet. Most major differences have arisen from their difference in size and mass. The Moon, with less surface gravity, has allowed its atmosphere and water to evaporate. The Moon's small size has allowed it to cool much more rapidly leaving it a solid and geologically dead planet. Due to the lack of an atmosphere and any recent geological activity, the Moon's cratered surface has remained relatively unaltered in the last 3 billion years. The lunar surface has been dated by counting meteorite impact craters in various size ranges. Ancient surface is more saturated by craters than young surface. It has been determined that the lunar cratering rate was intense immediately after the Moon formed, and has since decreased steadily with time over a period of about 1 billion years. The largest meteorite impacts excavated the large lunar basins, which filled in with volcanic lava, forming the dark maria that we see today between the lighter and heavily cratered highlands. The most favored theory for the formation of the Moon is that an asteroid slammed into the Earth and formed a ring of debris close to the Earth, out of which the Moon condensed. The mutual gravitational force between Earth and Moon produces tidal bulges on both sides of each body, in land, and, in the case of the Earth, the seas.

Key Words & Phrases

1. **Anorthosite -** a low density and light-colored silicate found in the lunar highlands, similar to the rocks composing some of the oldest mountain ranges on Earth
2. **Basalt -** the darker and denser silicates formed from cooling lava in the lunar maria and in lava flows on Earth
3. **Breccia -** rocks formed from individual, heterogeneous rock fragments welded together to form single rocks by meteorite impacts
4. **Highlands -** the heavily cratered surface of the moon, 4 to 6 kilometers above the elevation of the average lunar surface. The highlands cover roughly 85% of the lunar surface.
5. **Maria** – the smooth, dark regions of the lunar surface. The maria are 2 to 5 kilometers below the average elevation and cover approximately 15% of the lunar surface.
6. **Planetesimals** – the small bodies in the early solar system that coalesced to form planets
7. **Rays** -- bright streaks of fine material thrown across the surface of a planet as a result of an impact cratering event
8. **Refractory** – a substance that requires a very high temperature to be vaporized (iron for example)
9. **Synchronous rotation -** the rotation of a planet or satellite at the same period as its orbital period so that it keeps one side facing the object that it orbits

10. **Tides -** a raising and lowering of the Earth's oceans and solid surface caused by the difference in the Moon's gravitational force between the side of the Earth nearest the Moon and the side farthest from the Moon
11. **Volatile** – a substance that vaporizes at a relatively low temperature (water for example)

Review for Understanding

1. Outline the major theories of lunar evolution. Give the pros and cons of each.
2. Explain, using a diagram, the mechanism causing the tides. Show the configuration of the Sun, Moon, and Earth resulting in maximum tides.
3. How do we know that the maria are younger than the highlands?
4. Describe the three major types of lunar rocks.
5. What is synchronous rotation? Why is the Moon a synchronous rotator?
6. Why is the Moon less geologically active than the Earth?
7. Why does the Moon have no significant atmosphere?

Essay Questions

1. Describe the gross features of the Moon and explain how they help us to determine its history.
2. Explain how the Sherlock Holmes quotation at the beginning of this chapter relates to theories of the Moon's origin.
3. Describe the differences between landforms on the Earth and Moon. What are the reasons for these differences?
4. ~~Lunar surface dating exercise?~~

Chapter 9 - The Terrestrial Planets and Their Satellites: Why are they Different?

Lowell always said that the regularity of the canals was an unmistakable sign that they were of intelligent origin. This is certainly true. The only unresolved question was which side of the telescope the intelligence was on.
-- Carl Sagan, Cosmos, 1980

Chapter Preview

In addition to the Earth and Moon, the other terrestrial planets are Mercury, Mars, and Venus. By comparing these disparate worlds one can gain insight into the processes that made and modified their surfaces: volcanism, plate tectonics, erosion by wind, water, and ice, and chemical alteration. One can examine how these mechanisms are determined or influenced by the size of a planet, its distance from the Sun, and the presence of a significant atmosphere, which itself is determined by the gravitational force at a planet's surface.

Chapter Photo. *Sunrise at Mercury. From nrl.navy.mil*

Key Physical Concepts to Understand: *comparative planetology of the terrestrial planets, correlation of the characteristics of planets with their size and heliocentric distance, evolution of the Martian atmosphere*

I. Introduction

In this chapter we will study the three terrestrial planets, other than the Earth: Mercury, Venus, and Mars. In an attempt to understand how planets form and evolve, we will compare them with the Earth and Moon and examine how their properties correlate with their size and distance from the Sun.

II. Mercury

Mercury is the closest planet to the Sun. Because of its small size, 2/5 the diameter of the Earth, and nearness to the much brighter Sun, it is usually difficult to see without aid of a telescope. At those times when it's separation from the Sun is at maximum it can be seen with the naked eye close to the Sun either shortly after sunset or before sunrise. Mercury, named for the Roman god who acted as the messenger of the gods, zips around the Sun with a period of 88 days, but rotates on its spin axis only once each 59 days.

Table 9.1: *Bulk Properties of Mercury*

Property	Measurement
Mass	0.055 M_{Earth}
Radius	2439 km
	0.382 R_{Earth}
Average Density	5430 kg/m^3
Average Distance from the Sun	0.387 AU
Orbital Period - Sidereal	88 Earth days
Orbital Eccentricity	0.206
Sidereal Rotational Period	58.7 Earth days

It wasn't until 1974 that detailed photos were made of Mercury's surface with the Mariner 10 spacecraft (Figure 1). Mercury's cratered surface appears somewhat similar to Moon, but there are no lunar-like maria on Mercury, only broad plains between craters. Presuming that maria formed on Mercury as they did on the Moon, cratering must have occurred after Mercury's maria formed, leaving no smooth maria but cratered plains between the Mercurian highlands.

Figure 1. *A comparison of the surfaces of Mercury, Venus, Earth, and Mars (to scale). The images of Mercury, Earth and Mars are true-color images. The Venus image is*

constructed from Magellan spacecraft radar imagery and shows topographical features with shades of red (false-color).

The most dramatic feature on the surface of Mercury is the Caloris Basin (Figure 2), 1300 kilometers in diameter, surrounded by a 2 kilometer-wide rim of mountains, which is in turn surrounded by plains. In the interior of the Caloris Basin are a few, widely spaced craters indicating a relatively young, lightly cratered surface. The impact that formed the Caloris Basin also caused a wrinkled hilly region directly on the opposite side of the planet covering one-half million square kilometers (Figure 3).

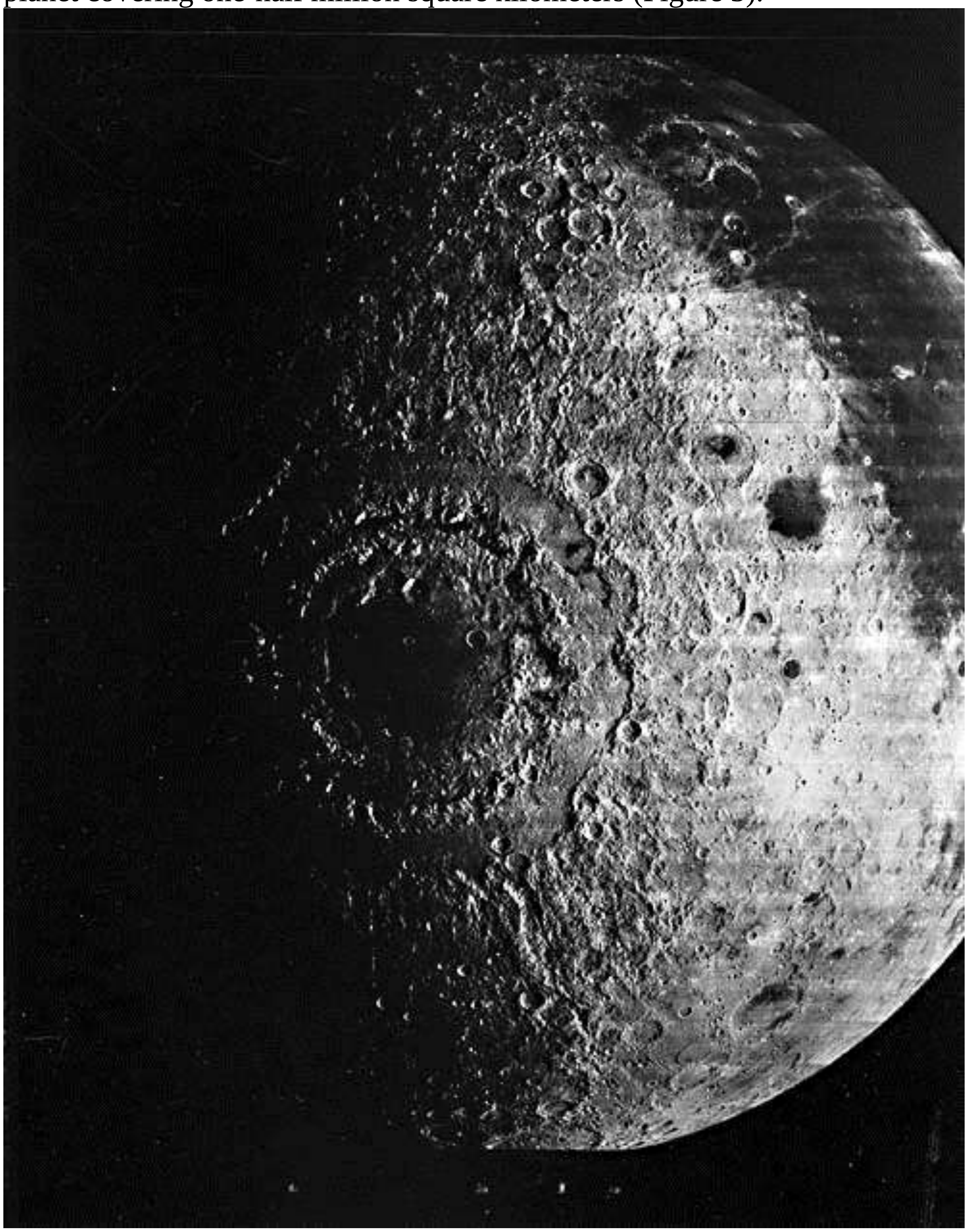


Figure 2. *A Mariner 10 spacecraft image of Mercury. NASA.*

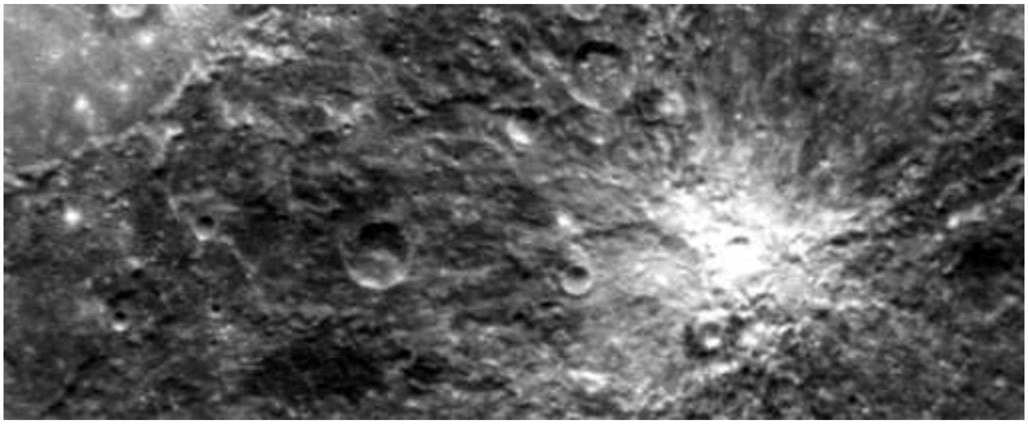


Figure 3. *The surface of Mercury antipodal (opposite) to the Caloris Basin. NASA.*

Mercury is covered by gently rolling plains and **scarps**, or cliffs (Figure 4) which indicate a thin lithosphere that cracked as Mercury cooled and contracted. This lack of geological activity suggests that Mercury is covered by a thick crust. Scarps are thought to have formed by the solidifying and shrinking Mercurian core and mantle, that rumpled the surface like a orange shrunken and wrinkled in the hot Sun.

Figure 4. *A scarp on Mercury's surface. A scarp, or cliff, 1 km high and 100 km long cuts through several craters on the surface of Mercury. (NASA)*

At 5% of the mass of Earth, Mercury has no atmosphere except for hydrogen and helium boiled from Sun and subsequently impacting Mercury's surface and absorbed by surface rocks, and sodium and potassium that were ejected from surface rocks when they were hit by the solar wind. Mercury has a density of 5430 kg/m^3, close to Earth's (5520 kg/m^3). Both Mercury and Earth have high density iron cores. The Earth's greater mass compresses it giving it a slightly higher density. Models of Mercury's interior predict a mantle approximately 600 kilometers thick (Figure 5).

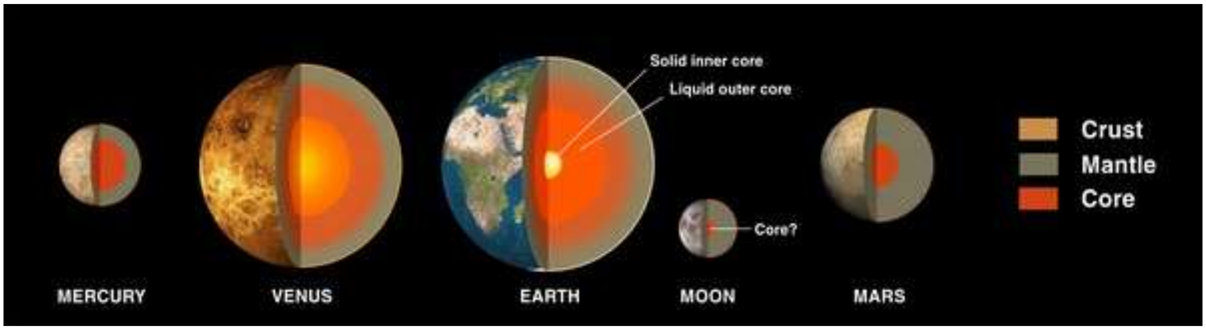


Figure 5. *Scale drawing of the interiors of Mercury, Venus, Moon, and Mars. From examiner.com*

Mercury is located close enough to the Sun so that it is not expected to contain low-density volatile materials. As a result, Mercury is the most iron-rich planet in the Solar System. Mercury's weak magnetic field (about 1% of the strength of the Earth's) and high density indicate that it has an iron core. It has not been settled whether Mercury's iron core is molten or solid.

Because of the extremely long day and closeness to the Sun, the surface temperature of Mercury varies wildly, from 700 K (800° F) to 100 K (-280° F). This compares to a typical 11 K variation between night and day for a location on Earth.

In 1991 Caltech scientists used radar to determine that Mercury's north polar region is highly reflective. Polar areas are deeply shadowed from sunlight and are therefore extremely cold. It is presumed that the highly reflective polar cap is indicative of a water ice cap. Even though the daytime surface of Mercury can be extremely hot, the north polar region is cold enough to support the existence of water ice.

III. Venus

Venus can be regarded as the Earth's twin, with nearly the same size, density, and mass as the Earth (Figure 6). But it is nearly one-third closer to the Sun. Venus appears to have twice the maximum angular separation from the Sun as Mercury. Venus is second in brightness only to Sun and Mercury and can often be seen during the day.

Figure 6. *An ultraviolet image of Venus taken by the Pioneer orbiter shows the global cloud patterns in the planet's upper atmosphere. Surface features are hidden from view by the opaque Venusian atmosphere.* **(NASA).**

The Venusian surface is permanently overcast with clouds, so that the surface cannot be seen in visible light. In the 1960s the Soviets and US sent probes to inspect Venus. Soviet probes penetrated the atmosphere. In 1970 a Soviet probe survived the high surface temperature and corrosive atmosphere, measuring surface temp of 750 K (900 F) and pressure of 98 bars (14.7 pounds of force/inch^2, equivalent to a depth of nearly 1 kilometer under water).

Table 9.2*: Bulk Properties of Venus*

Property	Measurement
Mass	0.815 M_{Earth}
Radius	6051 km 0.949 R_{Earth}
Average Density	5250 kg/m^3
Average Distance from the Sun	0.723 AU
Orbital Period - Sidereal	224.7 Earth days
Orbital Eccentricity	0.007
Sidereal Rotational Period	243 Earth days retrograde

Venus is covered by a 20 kilometer-thick layer of clouds, below that is 20 kilometers of haze, covering about 30 km of clear atmosphere (Figure 7). Due to slow rotation, there is insignificant coriolis force, and therefore no cyclonic cloud patterns. Clouds appear yellow to yellow-orange from sulfur compounds. Sulfur dust is detected in the upper atmosphere, sulfur dioxide and hydrogen sulfide at lower levels. Clouds are composed of concentrated sulfuric acid. Because of the high atmospheric pressure, rain does not fall; instead there is a perpetual mist. Sulfur compounds found in the atmosphere must constantly be replenished from volcanic activity. Radio bursts associated with lightning in what may be volcanic plumes are heard.

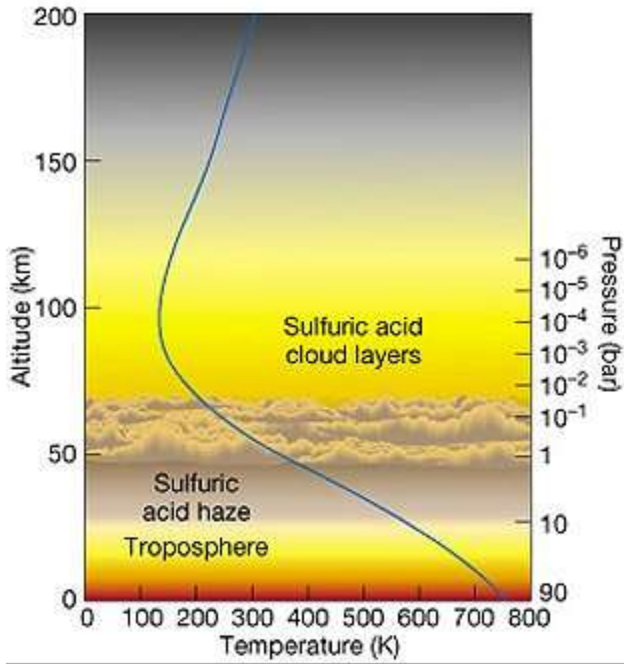


Figure 7. *Diagram of the Venusian atmosphere as measured by Pioneer and Venera probes that were dropped into the atmosphere. The blue line shows the measured temperature versus altitude in the atmosphere. High temperatures beneath the clouds are due to an intense greenhouse effect.* **(daviddarling.info)**

The surface of Venus is hotter than the surface of Mercury, even though it is farther from the Sun, due to the Greenhouse effect from carbon dioxide in the Venusian atmosphere. One importance of studying Venus is to use it as a laboratory for studying the effects of atmospheric pollutants on the Earth's climate.

A question of major importance is: "How much carbon dioxide causes how much heating on the Earth?" The difference in Venus and Earth is that much of Earth's carbon dioxide has dissolved in its oceans or has been converted by organisms into sedimentary limestone (such as chalk). It is too hot on Venus to condense oceans from volcanically emitted water. As a result a massive atmosphere must have developed with no oceans. Where did Venus' water go? Either sunlight broke up any water that it possessed into hydrogen and oxygen, which was later lost into space, or Venus formed with little water to begin with because it is so close to the Sun.

Ninety-six percent of the Venusian atmosphere is carbon dioxide and 4% is nitrogen. Although much light is reflected from the clouds of Venus, its surface is even hotter than Mercury. Without the greenhouse effect the temperature of Venus would be about 465 K instead of 750 K at noon. The night side is about the same temperature as the day side.

The first detailed image of the Venusian regolith was taken in 1981 by a Soviet lander (Figure 8). A thin layer of lava is seen, fractured into thin rounded rocks, similar in appearance to lava basalt flows on the Earth and Moon. The seventh lander site showed a more granite-like composition similar to Earth's continental rocks.

Figure 8. *A Soviet Venera image of the surface of Venus, taken in 1982. Part of the Venera lander is seen in the lower right of the image.* **(NASA)**

The Magellan spacecraft arrived at Venus in 1990 to map the Venusian surface using radar. Radar mapping of the planet produced a 3-D profile of surface from the time delay between the emission of a pulse of radar and its detection (Figure 9). The interval between emission and detection, back at the spacecraft, is determined by the distance that the radar beam travels to the Venusian surface and back again. The higher the altitude of the surface from which radar is bounced, the shorter the time delay between emission of a radar pule and its reception. An altitude map of the planet was constructed with 100-meter resolution. One result of the Magellan mapping is that Venus was discovered to be very flat compared to the Earth. Eighty percent of the Venusian surface is lava plains and rolling hills.

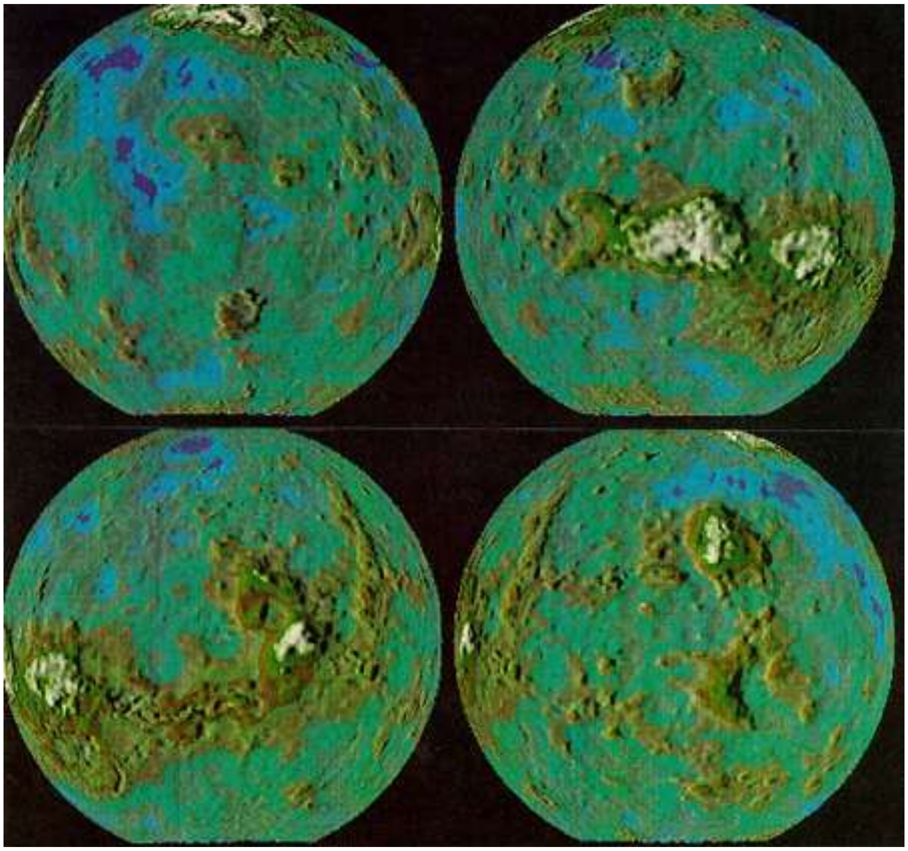


Figure 9. *Radar images of Venus. Color corresponds to elevation. The radar map of Venus was produced from Pioneer orbiter data. From archive.ncsa.illinois.edu*

Venus has two large continental highlands. One, called Ishtar Terra for the Babylonian goddess of love, is found in the Northern Hemisphere. Ishtar Terra is approximately the size of Australia. Maxwell Montes (Figure 10) is the highest summit, 11 kilometers above the average elevation, compared with 9 kilometers for Mount Everest. The surface topography of Venus resembles Earth without an ocean filling in ocean basins. Ocean floors on Venus are composed of basaltic lava flows. Some trenches resemble sea floor trenches on Earth. However, no folded mountain ranges, produced by tectonic plate collisions, are found. There is little evidence of faults produced by sliding tectonic plates. It is straightforward to draw the conclusion that there is little evidence for plate tectonics on Venus. Either Venus (95% of Earth's diameter) cooled significantly faster than the Earth or the Venusian surface is more fluid from interior heating than the Earth is.

Figure 10. *Maxwell Montes, the tallest mountain on Venus. A reconstruction based on radar images. AOPD/NASA.*

The largest continent, Aphrodite Terra (Figure 11), named for the Greek goddess of love (Venus is the Roman name for Aphrodite), is found in the Southern Hemisphere. Aphrodite is half the size of Africa, and is covered by a web of fractures.

Fewer than 1000 craters were seen by Magellan radar on the surface of Venus, less than 1% of the number seen on the Moon and Mercury. Today, meteorites impacting the Venusian atmosphere are vaporized, but this shouldn't have inhibited large craters from forming before the atmosphere developed in the period of intense Solar System cratering. This low number of craters suggests that the plains are 500 to 800 million years old. This low density and the random distribution of craters indicates that Venus periodically erases its surface volcanically (there is no evidence of plate tectonics). With a thick 300-kilometer crust (Figure 5) there could be a half-billion year oscillation as internal radioactivity builds up heat in the interior and then heat is released. Such temperature oscillations could easily cause periodic volcanic activity of the type that would periodically erase nearly all signs of previous impact cratering.

Sulfur in the atmosphere and traces of recent volcanic activity indicate a molten interior. Since the density of Venus is the same as the Earth's, this should indicate a magnetic field. However, there is none due to the slow, 116.8-day rotation of the planet. The slight 3° axial tilt with respect to the planet's orbital plane means that there are no seasons on Venus. Because of the heavy Venusian cloud cover there is an insignificant day to night temperature differential as well.

Comparative Planetology: Surface appearance vs. Planet Size

In comparing the solid-surfaced planets, there are a number of observable properties that vary systematically with the size of a planet and its distance from the Sun. Examining the Moon, Mercury, Mars, Venus, and Earth (from smallest to largest) one notices that the smaller planets are more heavily cratered, less geologically active, and less eroded than the larger planets. What can we learn from these observations? The geological activity of a planet (volcanism and tectonic activity) is largely determined by the state of the planet's interior, basically how much of its volume is occupied by molten rock. Size is critical here. If we assume that shortly after planetary formation all of the terrestrial planets were completely molten owing to the energy given off by radioactive elements, then the current condition of a planet's interior is determined by the rate at which it cools. Here our own physical experience can be put into play.

Which cools faster a whole baked potato or a baked potato that has been cut into small pieces? The latter is obviously the case. People commonly chop food into small pieces to get it to cool faster. Why? The amount of heat contained in any object of given composition, density, and temperature is simply proportional to the volume of the object. Given two baked potatoes of equal temperature, one twice as large as the other, the larger potato will have twice the heat energy as the smaller one. However, the rate at which a potato cools is dependent not on its volume but on its surface area. Hot potatoes give off heat energy by heating the air around them and radiating infrared light. Both of these processes occur at the surface of the potato. The larger the surface area of the potato, the faster the potato will cool. The rate of heat loss is proportional to the surface area of the potato for a potato of given temperature. In other words, if we have two potatoes at the same temperature, one with twice the surface area as the other, the one with greater surface area is losing heat energy at twice the rate as the smaller one.

What happens as we cut a hot potato into pieces? The total amount of surface area increases, enabling it to cool faster. Let us take a simplified and somewhat ideal case. We'll start with a cubic potato ~~(Figure 14)~~ and divide it into 27 equal cubic pieces, each piece having sides that are one-third the length of the original cubic potato and 1/27th the volume of the original. Each cube has six sides with 1/9th the area of the area of a side of the original potato (1/3rd of the length times 1/3rd of the width equals 1/9th of the area). The surprising result is that that *each* of the smaller clones of the original cube have 1/9th the surface area of the original. The total surface area is 27 times this, or 27 x 1/9th the original surface area, which equals 3 times the surface area of the whole cubic potato. By dicing the potato it will cool at least 3 times faster! (Actually it cools more than three times faster, because it takes less time for heat to be conducted from the interior of the small pieces to their surfaces than it does for the single large piece.) By extrapolating from potatoes to planets one can see that smaller planets, like the Moon and Mercury should cool much faster than the Earth and Venus. It should then not be much of a surprise that the Moon and Mercury have little evidence of volcanism, tectonic activity, large molten cores, or significant magnetic fields and that Venus and Earth have significant volcanism, tectonic activity, and significant molten cores. Mars is in between, showing large volcanic mountains but no evidence of plate tectonics or a substantial magnetic field.

Comparative Planetology II: Existence of atmosphere, size, and distance from sun.

The existence of a substantial atmosphere on a planet is determined largely by the planet's surface gravity and temperature. The former is dependent on the planet's density and size (Figure 11), the latter on its distance from the Sun.

Whether or not a planet can retain a massive atmosphere is dependent on whether or not the velocity of the gas molecules constituting that atmosphere can reach the escape velocity for the planet (review Chapter 7 Section VII). The velocity of molecules, in turn, is determined by their mass and the temperature of the atmosphere. The lighter a molecule is the faster it travels. The higher the temperature of a gas, the faster its constituent molecules will travel. By heating an atmosphere the velocity of the molecules contained in the atmosphere will increase. First the light molecules, such as hydrogen and helium, will boil off, as they begin to reach escape velocity. If the temperature of the atmosphere continues to increase, more massive molecules, such as oxygen and carbon dioxide, will leave as well. Although the existence of an atmosphere can *cause* the surface temperature of a planet to be larger than it would be otherwise through the greenhouse effect, this is in turn dependent on the composition of the atmosphere.

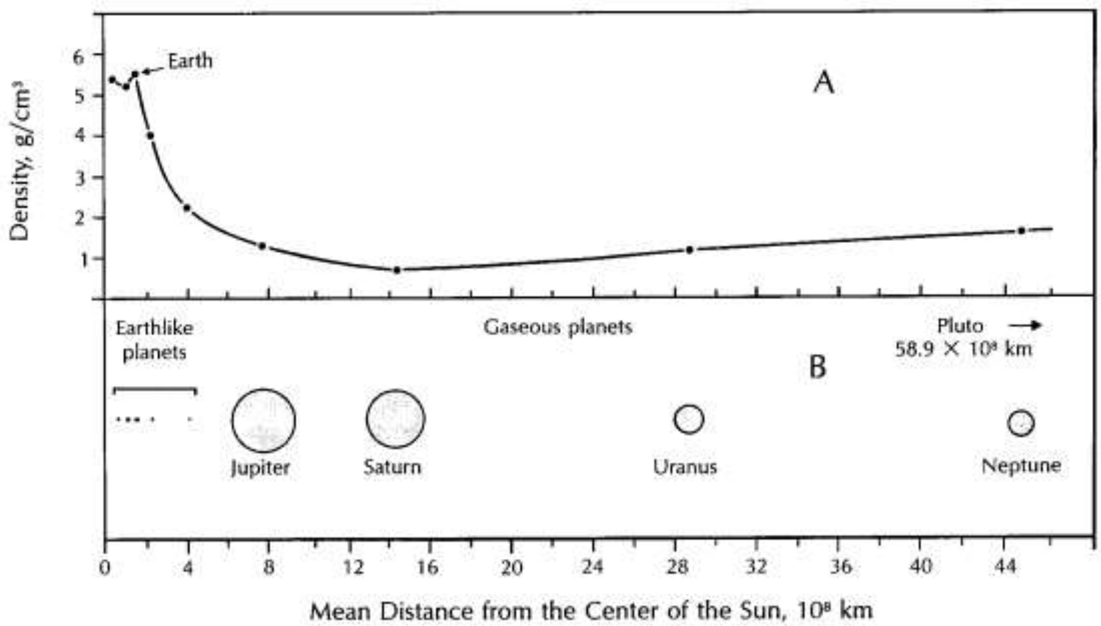


Figure 11. *The density of planets decrease, in general decreases with distance from the Sun, reflecting the temperature at which they condensed. Planets at the distance of Jupiter and Saturn were able to condense more volatiles, like hydrogen, helium, water, and methane. From unc.edu*

Let's perform a thought experiment for the purpose of illustration of the effect of surface gravity and heliocentric distance on a planet's atmosphere. To simplify matters, assume that that the terrestrial planets all began with dense primitive atmospheres, all with the same composition. Since the Sun and most massive planets have large enough surface gravity to hold captive even the lightest gas, hydrogen, we can assume that early primitive planetary atmospheres were probably similar in composition to the Sun and gas giant planets: rich in hydrogen and helium with trace amounts of the other elements. The surface temperature of a terrestrial planet would be dependent on the distance of the planet from the Sun, with Mercury having the highest surface temperature. One would then assume that the planets closest to the Sun and the lowest surface gravity would then have the least significant atmospheres. Indeed, the two terrestrial planets with the least significant atmospheres are the two least massive planets with the least surface gravity: the Moon and Mercury. The Earth and Venus have the largest surface gravities among the terrestrial planets. Mars again, is in between and as a result has a significant atmosphere, barely. The effect of distance from the Sun is not obvious with this group of inner planets, Mercury is the closest planet to the Sun, but Mars, a planet with a sparse atmosphere is far from the Sun. We will see an effect of heliocentric distance in Chapter 10, when we study the atmospheric composition of some of the larger satellites of the gas giants, Titan and Triton in particular which are comparable to the Moon and Mercury in mass and surface gravity.

IV. Mars

Mars, the red planet, named for the Roman god of War, is the only planet that can be resolved from Earth using a simple telescope. Mars, although known to ancients, was first seen through a telescope by Galileo in 1610. The Dutch physicist Huygens first used a telescope to measure the rotational period of Mars. He observed a dark surface feature that moved across the Martian surface with a period of about 24 hours. The Italian astronomer Cassini determined, more accurately, a period of 24 hours 37 minutes. In the 1700s and 1800s telescopes enabled astronomers to see shrinking and growing white polar caps, dark areas that could be mistaken for oceans, reddish desert-like terrain, and changing streaks (increasing in prominence and size in summer). More prominent dark areas were thought to be regions covered with vegetation. In 1877 the Italian astronomer Shiaparelli discovered forty or so linear markings on the Martian surface which he called *canali*, Italian for water channels. This unfortunate choice of terminology framed subsequent discussions of the Martian surface, in which these markings were called canals. This fired the imagination of many people. In particular, Percival Lowell, from a wealthy Boston family, built Lowell Observatory near Flagstaff Arizona in 1895, primarily for the purpose of studying Mars. Lowell mapped 160 of these linear features, or canals on the Martian surface (Figure 12).

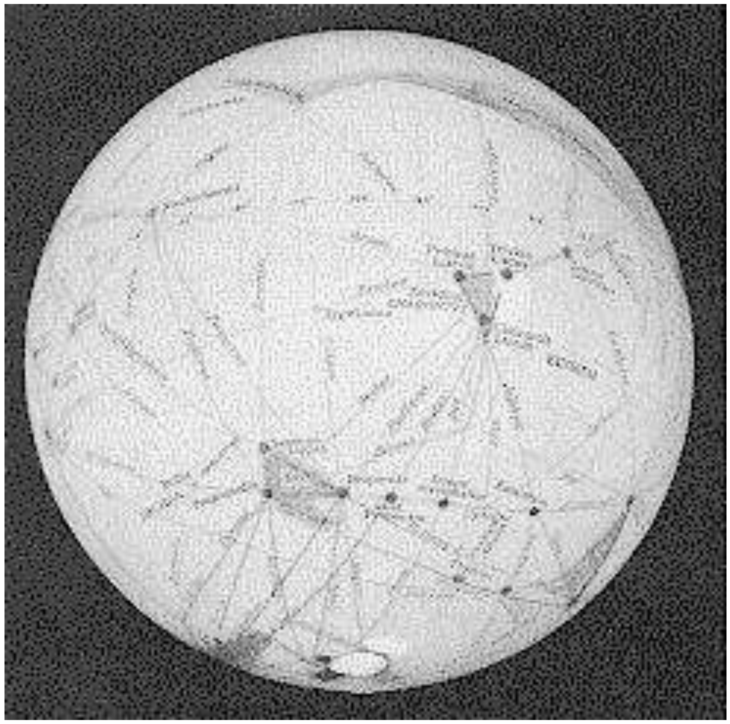


Figure 12. *A sketch of the canals on Mars made by Percival Lowell in ???*

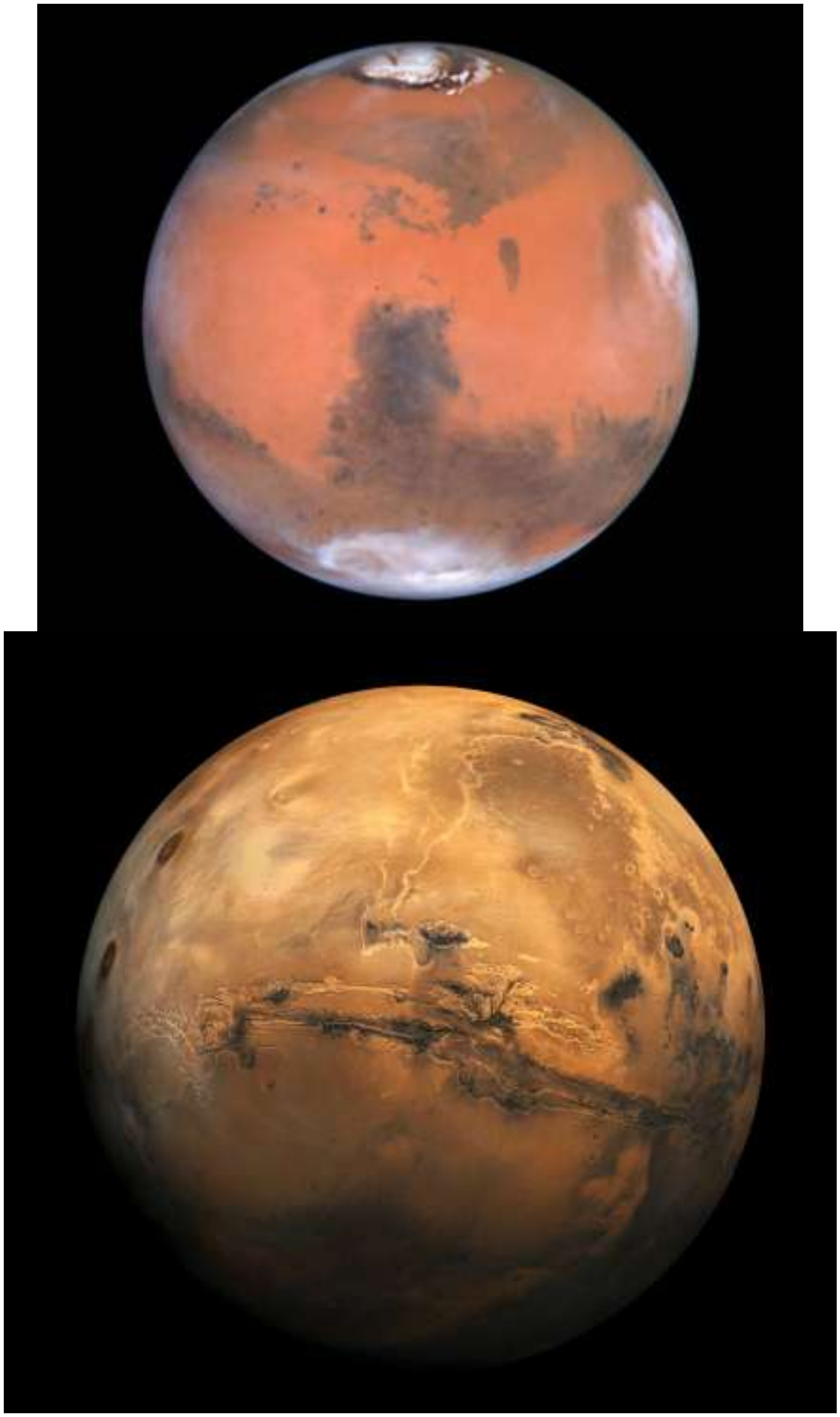


Figure 13. *Some of the highest quality images of Mars.* **Panel A.** *Hubble Space Telescope image of Mars taken near its closest approach to Earth. The north polar ice caps* smaller than the south polar ice cap owing to the seasonal variation in the size of the polar caps. **Panel B**. Viking orbiter image of Mars with the Valles Marinaris valley showing prominently. (NASA)

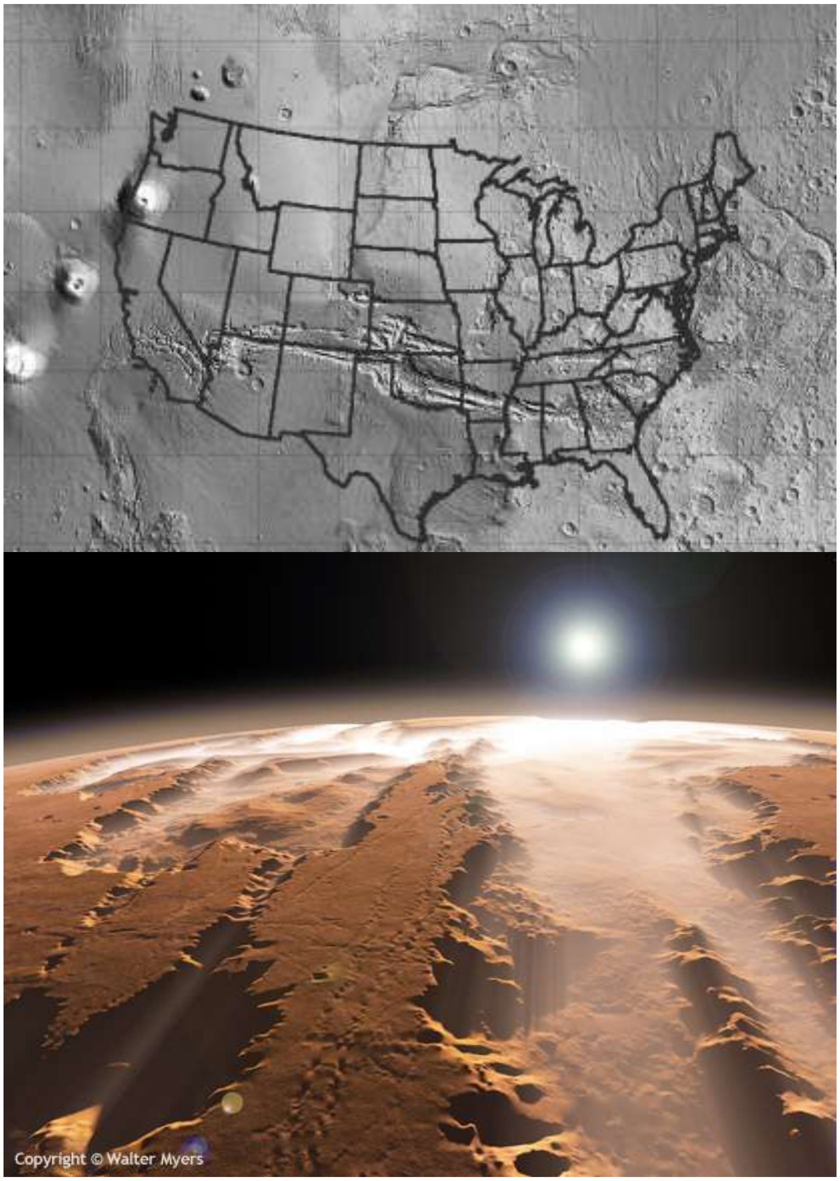


Figure 14. *Valles Marineres. Upper Panel: As seen in the previous figure, the Mariner Valley dwarfs the Grand Canyon. It is shown with a map of the US overlaid for a size comparison. Lower Panel: a high resolution image from Mars Orbiter imaging. (NASA)*

Figure 15. *The Martian moons Phobos and Deimos. NASA*

Lowell proposed that the Martian canals were a vast irrigation system and that the seasonal changes in appearance of the Martian surface were seasonally varying vegetation. The changing appearance of the north polar cap was associated with seasonal melting of a water ice cap. Water from melting polar caps could be transported by intelligent beings to the desert-like terrain nearer the Martian equator for the purpose of irrigating crops. These conclusions, based on the canali first seen by Shiaparelli spawned a science fiction genre, which lasted for half a century. Now that spacecraft have orbited Mars and landed on its surface it is natural to ask, are these canals real surface features or not? What are they? There is no clear answer. Three US spacecraft visited Mars during the 1960s; they viewed many flat-bottomed craters, volcanoes, canyons, and the polar ices caps, but nothing consistent with the canals seen and sketched by Percival Lowell (Figures 13 & 14). Although there are no clear linear surface features associated with maps of canali made by Lowell and others, the Martian surface is marked by transient wind streaks that could possibly be mistaken for canals by telescopic observers. It is also a possibility that the tendency of the human mind to see patterns in images, even when they are not really there, is the real culprit. As Carl Sagan put it, **"***Lowell always said that the regularity of the canals was a unmistakable sign that they were of intelligent origin. This is certainly true. The only unresolved question was which side of the telescope the intelligence was on."*

Mars has two small moons, Phobos and Deimos (Figure 15). Due to their small size and orbits close to the surface of the planet, they were only discovered in 1877 by the American Astronomer Asaph Hall. Their small size and irregular shape lead astronomers to believe that they are captured asteroids.

Table 9.3: *Bulk Properties of Mars*

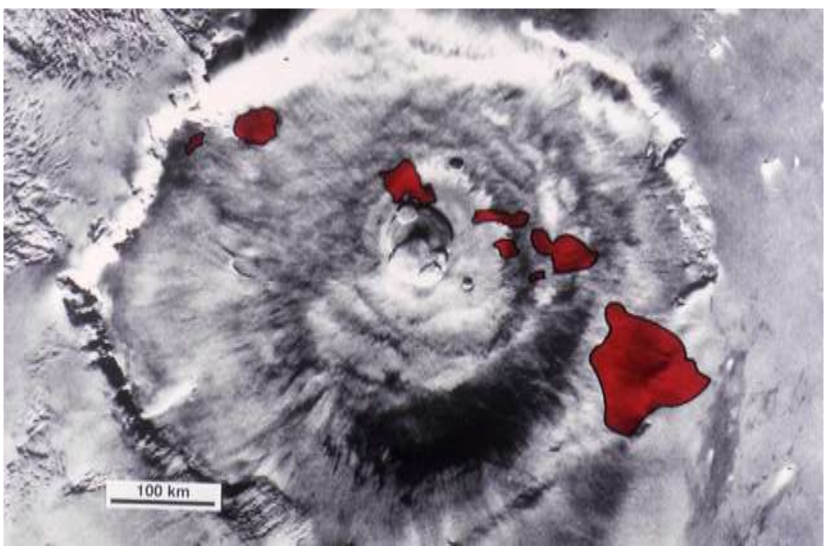
Property	Measurement
Mass	0.107 M_{Earth}
Radius	3393 km
	0.532 R_{Earth}
Average Density	3950 kg/m^3

Average Distance from the Sun	1.52 AU
Orbital Period - Sidereal	687 Earth days
Rotational Period - Sidereal	24 h 37 min
Orbital Eccentricity	0.093
Sidereal Rotational Period	27.3 days

WebVideo: Missions to Mars http://www.youtube.com/watch?v=veFfOSTy0ZY

Martian craters are noticeably different than those on the Moon and Mercury, both qualitatively and quantitatively. The density of small craters is substantially lower on Mars than on the Moon. Craters are heavily eroded by dust storms resulting from high winds, which occasionally cover the entire planet in a shroud of dust. In particular, Martian storms fill in low spots with wind-blown dust. Because of the thin atmosphere, craters have not been completely eradicated to the extent that they have on the Earth. The most heavily eroded surfaces on Mars are typically no older than 100 million years while the most heavily cratered regions are estimated to be several billion years old, still much younger than the 3.6 billion year old surface of the Moon.

In 1971, the Mariner 9 Orbiter produced the first detailed high-resolution pictures of the Martian surface, allowing us to see for the first time the most enormous volcanoes and canyons in our Solar System. Olympus Mons, for example, is a shield volcano as big as a western state, rising 24 km above the surrounding plains, some 3 times the height of Mt. Everest (Figure 16).



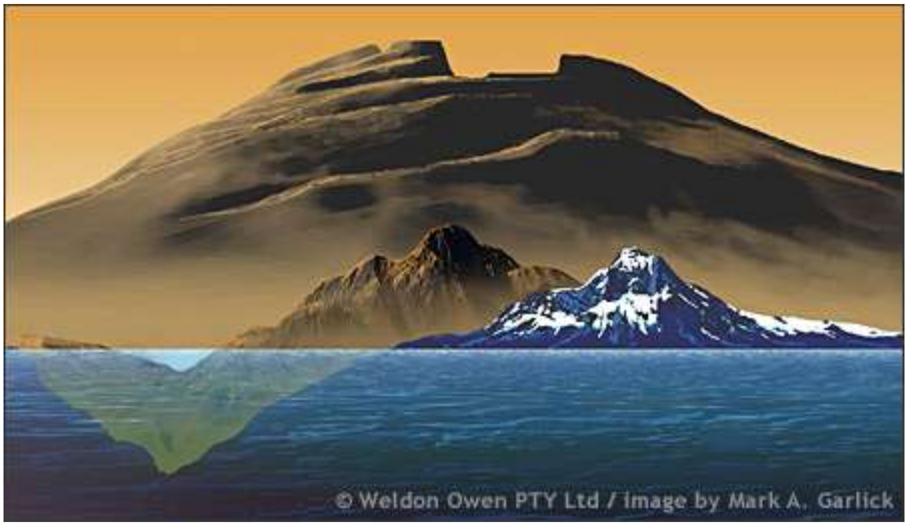


Figure 16. *The largest mountain on Mars (Olympus Mons, or Mount Olympus). In the Upper panel the size of Olympus Mons is compared with the Hawaiian Islands. From* *http://blogs.agu.org/martianchronicles/2009/05/23/olympus-mons-is-how-tall/*
In the lower panet Olympus Mons is shown to be considerably larger/taller then the tallest mountains on Venus, and Earth (Mount Everest). From *http://blogs.agu.org/martianchronicles/2009/05/23/olympus-mons-is-how-tall/*

What is it about Mars that produces these enormous volcanoes? Some of the largest volcanic mountains on Earth are chains of mountains, such as the Hawaiian Islands (Mauna Kea is actually the largest mountain on Earth when measured from the floor of the Pacific) and the Aleutians. These chains represent hot spot volcanoes. Lava rises from depth over a hot spot in the underlying asthenosphere at a tectonic plate gap or boundary (Figure 17). Lava flows to the surface building a volcanic mountain. If the overlying tectonic plate is in motion (the Earth's plates typically move several centimeters per year) then previously formed volcanic mountains will move away from the hot spot in time and a new volcanic mountain will be built. The result is a line or chain of mountains with the oldest at one end of the chain and the youngest at the other end, nearest to the hot spot. Since Mars has only one-half the radius as the Earth, it has cooled more rapidly, resulting in a thicker crust and less geological activity. There is no evidence of any plate tectonics. It is reasonable to assume that on Mars volcanic activity and mountain building have occurred at stationary positions on the Martian surface rather than at moving plate boundaries, as happens on Earth. This would result in very large single mountains rather than chains of more modest-sized mountains.

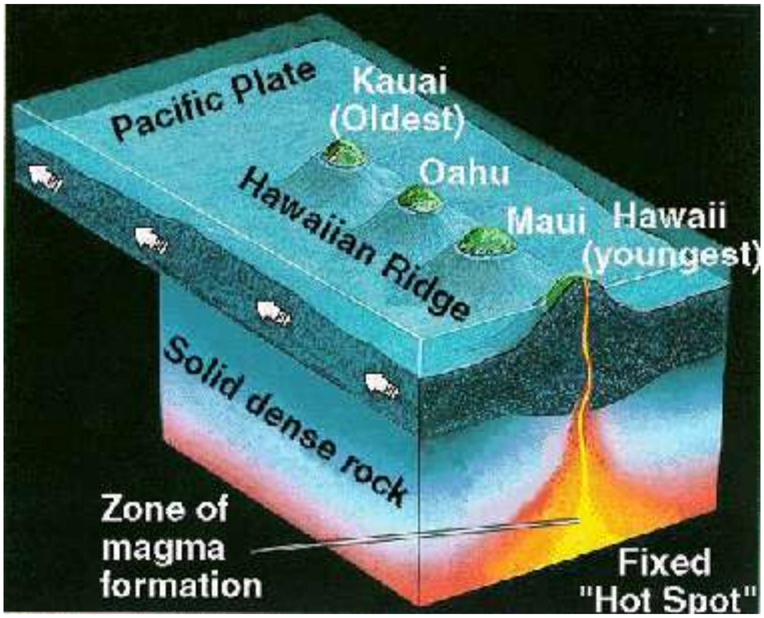


Figure 17. A diagram showing the formation of the Hawaiian Island chain over time as the overlying pacific plate moves with respect to a fixed volcanic hot spot. From volcano.oregonstate.edu

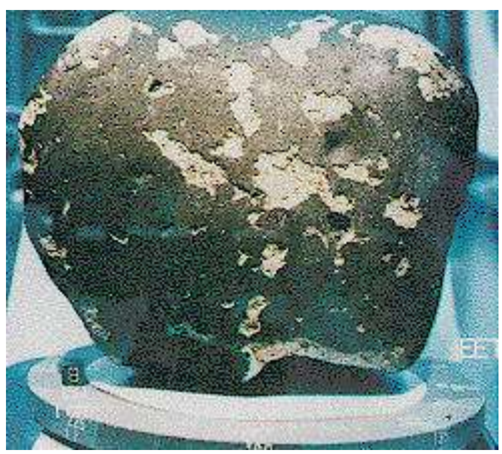


Figure 18. *SNC meteorite. FMW 200-9.22*

Another geological peculiarity is that most Martian volcanoes are found in the Northern Hemisphere and most craters are found in the Southern Hemisphere. A huge canyon runs parallel to equator, Valles Marineris (Figure 14), named after the Mariner spacecraft that produced the first close-up images of the planet. Valles Marineris dwarfs the Earth's Grand Canyon with a length of 4000 kilometers and a width of 100 kilometers. This may be an ancient tectonic feature. Other features resemble dry river valleys on Earth, complete with tributaries and streambeds meandering around ancient craters (Figure 19). Theses features, perhaps 1 to 3 billion years old, seem to indicate that water once flowed on the surface of Mars. Today there is no evidence of surface water; the atmospheric pressure is low enough that any liquid water placed on the Martian surface would immediately boil. Water does seem to exist in solid form at the polar caps where the temperatures are less than 150 K (-184° F), cold enough for carbon dioxide to exist in solid form (dry ice). It is possible that sometime in the history of the planet energy from a meteorite impact or volcanic activity melted water at the poles, which temporarily released liquid water onto the Martian surface, producing these riverbeds.

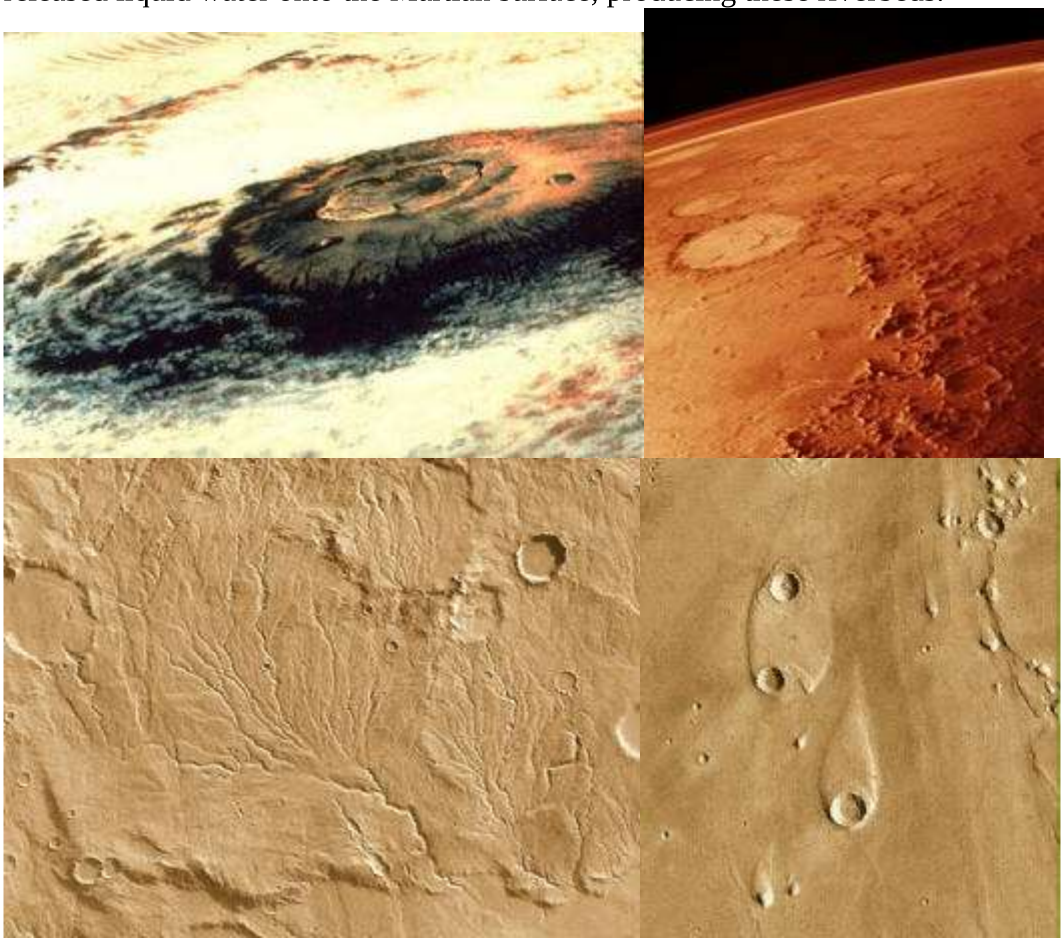


Figure 19. *A montage of Mars images.* ***Panel A.*** *The largest known volcanic mountain in the Solar System, Olympus Mons, rises 24 km above the Martian surface and is surrounded by a halo of clouds created by upslope winds. The summit consists of a number of overlapping volcanic craters, 70 km in diameter.* ***NASA*** ***Panel B.*** *An image of the Martian surface showing craters, hills, and a portion of the Martian atmosphere above the horizon.* ***NASA*** ***Panel C.*** *Dendritic channels on the Martian surface providing evidence of flowing water in the past.* ***NASA*** ***Panel D.*** *An image of a major flow channel with teardrop islands where water has evidently flowed around elevated crater walls, forming a streamlined shape.* ***NASA***.

The Martian polar caps have two components: a permanent water ice cap covered by a seasonally varying carbon dioxide layer (dry ice) (Figure 20). Each cap is 3000 to 4000 kilometers across in the winter. During the northern summer, the northern polar cap shrinks as it **sublimates** carbon dioxide from the solid state directly into the atmosphere. At the same time the southern cap is in the middle of winter and it is growing as carbon dioxide condenses directly out of the atmosphere. This procedure reverses itself in the northern winter. The maximum size of the southern polar cap is a little larger (4000 km) compared to the northern polar cap (3000 km) because Mars' elliptical orbit takes it closer to the Sun in northern winter than in does in southern winter.

Figure 20. *Ice and snow on Mars. In the upper panel one sees ice that has accumulated in the shaded/shadowed regions of an impact crater (the crater bottom and walls facing away from the Sun).*

Partly because Mars is only half the size of the Earth, its atmosphere is light, with a surface atmospheric pressure only 0.7% of that found at the Earth's surface. Mars has an atmosphere composed mainly of carbon dioxide (95%, the same percentage of the

Martian atmosphere as the Venusian atmosphere), with 5% nitrogen, argon, and oxygen. Argon is disproportionately abundant (1.6%) on Mars compared to the other planets. This is significant because argon, a noble gas, doesn't chemically combine with other elements to form compounds (similar to helium), and is heavy enough to resist being boiled out of the atmosphere. For these reasons the amount of argon present in a planetary atmosphere is indicative of the original mass of the planets atmosphere. In the case of Mars, the high argon abundance is indicative of an atmosphere with 10 to 100 times the mass of the current atmosphere; rivaling the Earth's atmospheric density. It is thought that sometime in Martian history Mars had a massive atmosphere composed mainly of molecular nitrogen and carbon dioxide and enough water to cover the entire planet to a depth of a few hundred meters.

Where did this primordial atmosphere go? Was it able to support life? If Mars was covered with water, where is it now? One possibility is that when the great volcanic mountain Olympus Mons formed, the Martian polar axis wobbled from an axial tilt of 45° to its current position, 25° with respect to the Martian orbital plane. A greater tilt of the Martian polar axis in the past would have produced more extreme seasons causing a more extreme summer shrinking of the polar caps, driving more water and carbon dioxide into the atmosphere. This would in turn produce a massive atmosphere with a large greenhouse effect, making Mars considerably warmer over the entire year. It is possible that it was warm enough that liquid water flowed on the planet. Now with a light atmosphere and colder surface, perhaps this water is frozen in an underground **permafrost** layer and at the polar caps as well.

High winds are common on Mars, with typical velocities of 17 to 50 kilometers per hour (Figure 21). These winds serve to erode the surface and transport wind-borne dust over the Martian surface. Surface temperatures are quite cold, -123° to –20° F in summer, and cold enough in winter to freeze carbon dioxide out of the atmosphere into solid form at the poles.

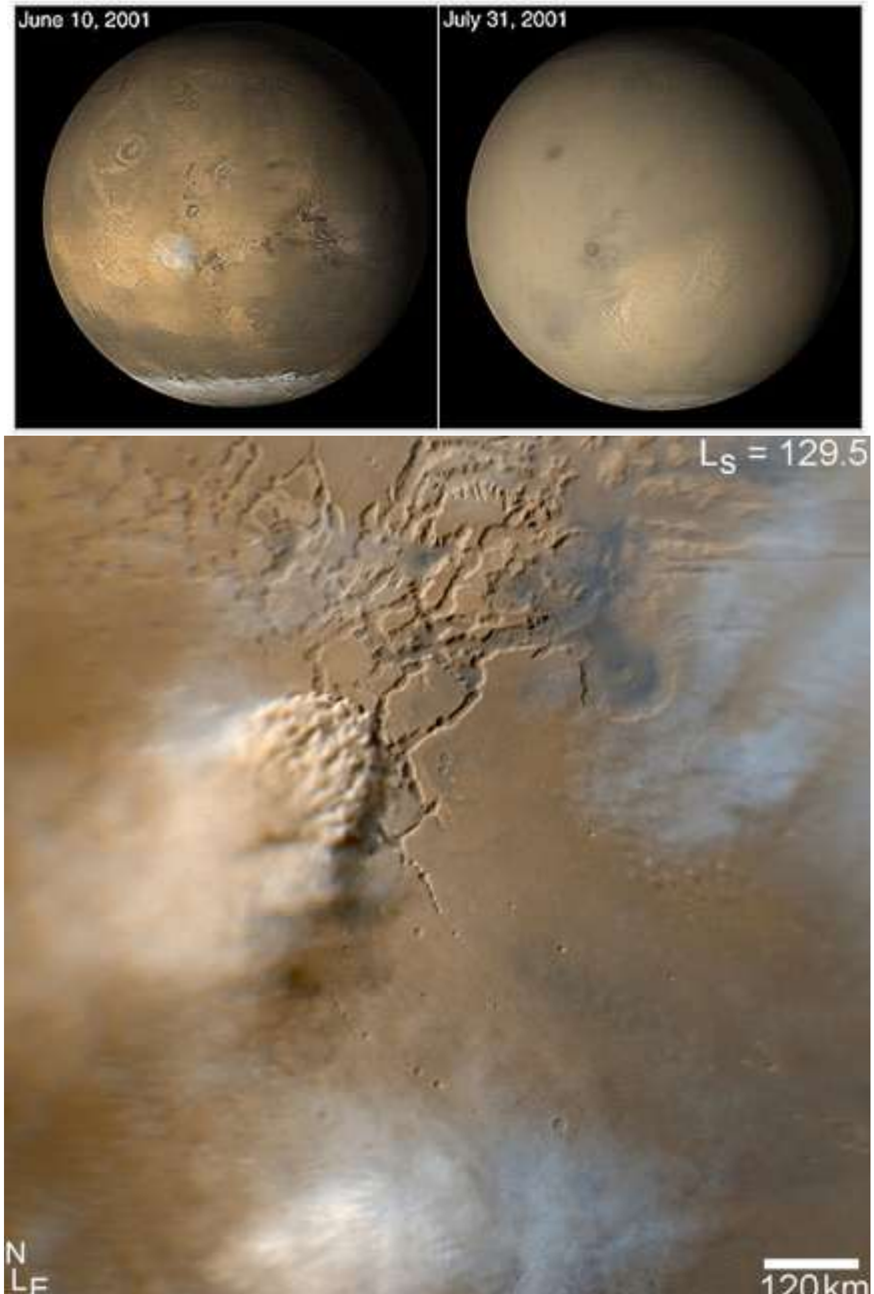


Figure 20. *Dust storms on Mars. The upper panel shows images of the planet Mars on two different dates, one where the Martian atmosphere is relatively clear and the other when the planet was shrouded in a global dust storm. The lower panel shows a more localized dust storm moving across the Martian surface. From*

A. Surface Geology

The US launched twin Viking spacecraft in 1975 motivated in part by the previous indications of water in the Martian atmosphere and an interest in exploring the red planet for life. Each spacecraft contained an orbiter and a lander (Figure 21). The Viking landers determined that the planet's red color is due to oxidized iron (rust) in surface rocks and dust. Much of the surface consists of iron-rich clay. The low density of the planet, 3950 kg/m^3, and the fact that no magnetic field was detected indicate that there is no iron core, rather that the iron in the planet is well distributed between the interior and surface. The only water detected on the surface is bound up in the crystal structure of the surface rocks.

Figure 21. *A Viking 2 Lander image of the Martian surface. The arm supporting the Viking weather station cuts through the center of the image.* **(NASA)**

An important component of the Viking lander experiments was the search for life. The Viking lander cameras saw no obvious signs of life. The landers were equipped to perform biochemical tests for the existence of microbial life. Each lander scooped up a soil sample and added water and nutrients. The samples were then monitored for biochemical reactions that would produce chemical byproducts. Chemical changes were seen, but are interpreted now as being solely chemical reactions between the Martian soil and the substances added by the landers. Although there is no evidence for present or recent microbial life on the Martian surface, this doesn't rule out the possibility of finding evidence in the subsurface or at the polar caps, where scientists suspect large deposits of water ice.

B. Martian Meteorites

In 1982 scientists discovered the first of the Martian meteorites or **SNC meteorites** (named for Shergony, Nakhla, and Chassigny, the sites where the first of these meteorites were found). (The Nakhla meteorite is the only meteorite to have produced a known fatality: it killed a dog on impact.) Up until this time no one believed that a meteorite impact could excavate material from the surface of another planet and launch it into space where the Earth could sweep it up. But the composition of trapped gases in SNC meteorites is identical to the composition of the Martian atmosphere. More recent calculations predict that about a half a ton of Martian meteorites impact the Earth each year. And although no Venusian meteorites have found to date, there is no reason to expect that they won't be.

In 1996, NASA scientists announced that they discovered potential microbiological fossils on the Martian meteorite ALH84001 collected in the Antarctic. High-resolution electron microscopy revealed tiny carbonate globules in the interior of ALH84001 resembling fossils of bacteria seen on Earth. Analysis ruled out that bacteria were introduced into the rock after it landed on Earth. If correct, this find would be the first positive detection of life external to the Earth, or extraterrestrial life.

One interesting issue raised in 1994 is whether life on Earth could have begun by its introduction via meteorite, or vice-versa: whether life on Earth could have contaminated Mars via Earth meteorites impacting that planet. Although life on a piece of ejected debris is expected to be harsh, during the actual excavation, through the interplanetary trip in the cold vacuum of space, and in the returning impact onto a planetary surface, bacteria can survive the trip. In particular, bacteria in space would survive in a freeze-dried state of hibernation indefinitely. As with most scientific discoveries the report of life in Martian meteorite ALH84001 provides more questions than answers.

Summary

The gross properties of the terrestrial planets differ largely because of size and distance from the Sun. The smallest, Mercury, is closest in properties to the like-sized Moon: no atmosphere, heavily cratered, and geologically dead. These are all properties of a planet that has evaporated its atmosphere, due to low surface gravity, and cooled quickly. This contrasts with the Earth and Venus, the largest terrestrial planets, which have retained heavy atmospheres and remained geologically active both in terms of volcanism and plate tectonics. Mars is the intermediate planet. In size and gross properties it is between the Earth and Venus on one hand and Mercury on the other. Mars has an atmosphere, although a very thin one. Wind and water erosion are evident, but so are ancient craters. Although Mars does not have multiple tectonic plates like the Earth, there is evidence of a single large crack in the crust out of which large volcanic mountains have formed. The densities of the terrestrial planets vary with heliocentric distance, with Mars and Venus having the highest densities, Earth and Mars the lowest. Studies of Venus and Mars are relevant to life on Earth. Venus is an example of a planet having experienced a runaway greenhouse effect that makes this planet completely inhospitable to life. Recent studies of an Antarctic Martian meteorite indicate that bacterial life may have been common on that planet, at least in the past.

Key Words & Phrases

1. **Permafrost**
2. **Scarp**
3. **SNC meteorite** – meteorites that are fragments of Mars, blown off its surface by cratering events (named for Shergony, Nakhla, and Chassigny, the sites on Earth where the first of these meteorites were found)
4. **Sublimate –** vaporize from the solid state to the gaseous state without first changing into a liquid

Review for Understanding

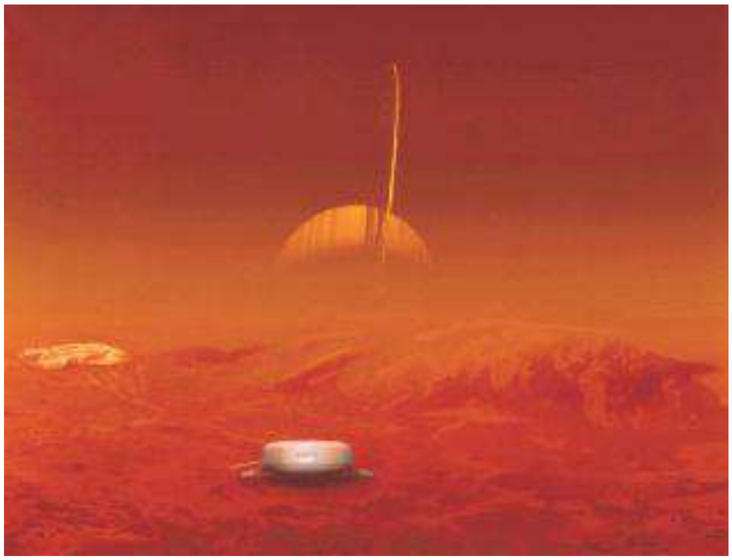
1. Why does Mars have the largest volcanic mountain in the Solar System?
2. Why do astronomers think that Mars once possessed a massive atmosphere?
3. What are SNC meteorites, and how did they come to be found on the Earth?
4. What causes seasonal variations in the Martian surface?
5. Why does Mercury not have any significant atmosphere?
6. Which terrestrial planet is likely to have the coolest core? Why?
7. Which element would boil off the surface of a planet first?

Essay Questions

1. Discuss in some detail how Mars is intermediate between the Earth and Moon geologically and the reason(s) for this.
2. What evidence is there for liquid water having flowed on the surface of Mars? Why is it not there now?
3. Discuss reasons for the difference in the appearance of the Martian and lunar surfaces.
4. What would the Earth's atmosphere be like if the Earth were much closer to the Sun (say as close as Mercury)? Much further (say it had formed at the distance of Jupiter)?
5. Compare and contrast Venus and Earth. What are the reasons for their differences?
6. Explain how volcanism, tectonic activity, magnetic field, existence of a molten core, and the size of a planet correlate.

Chapter 10 - The Outer Planets with their Rings and Moons

The principle of strategy is, having one thing, to know ten thousand things.
--Mussolini



Chapter Photo. *Artist's rendering of Saturn rising as seen from an observer on its largest moon Titan. From cvanepps.com*

Chapter Preview

The outer giant gaseous planets of our Solar System, Jupiter, Saturn, Uranus, and Neptune, provide 99.5% of the mass of all of the nine planets of the Solar System. They are so much larger and so unlike the inner terrestrial planets that were it not for the existence of life on Earth, the inner planets could be regarded as moon-sized objects left over from the formation of the Solar System. In some ways the gas giants are more similar to the Sun in structure and composition than they are to the other planets. Their large surface gravity has helped them to retain much of their original primordial atmospheres, rich in hydrogen and helium, a compositional mix like that of the Sun. Gravity has also enabled each gas giant to gather an entourage of satellites and ring material, orbiting the main body like a scaled-down version of the Solar System. Jupiter even emits its own radiation, generated by its collapse under its own gravity. Indeed, were Jupiter ten times more massive, such collapse would provide a hot enough interior for nuclear fusion to ignite in Jupiter's core, making it a star.

Key Physical Concepts to Understand: *density, the layout of the solar system*

I. Introduction

The outer part of our Solar System is wholly unlike the inner Solar System containing four gaseous giant (or Jovian) planets and Pluto, a solid-surfaced planet remarkably unlike the other four solid-surfaced planets. With the Sun, Jupiter dominates our Solar System containing 71% of the planetary mass (1300 Earth masses). The four Jovian planets together contain 99.5% of the masses of the combined planets; the terrestrial planets look like so much Solar System debris in comparison. Compared to the terrestrial planets the gas giants have extremely low densities, ranging from 700 to 1600 kg/m^3; if one could find a large enough body of water to hold it, Saturn would float. Jupiter and Saturn have approximately ten times the diameter of the Earth; Uranus and Neptune are somewhat smaller. The gas giants are composed mainly of the same gases that comprise the Sun, hydrogen and helium. No surfaces can be seen through the thick shroud of methane and ammonia ice clouds; instead the murky atmosphere becomes thicker with depth, becoming a gas denser than ???? Each of the Jovian planets reigns over an entourage of numerous satellites resembling mini- Solar Systems. Together these four planets have 129 moons with confirmed orbits, compared with three for the solid-surfaced planets. (The Earth has one and Mars has two.)

II. Jupiter

Table 10.1: *Bulk Properties of Jupiter*

Property	Measurement
Mass	318 M_{Earth}
Radius	71,490 km 11.2 R_{Earth}
Average Density	1330 kg/m^3
Average Distance from the Sun	5.20 AU
Orbital Period - Sidereal	11.86 Earth years
Orbital Eccentricity	0.048
Sidereal Rotational Period (Equatorial)	9 h 50 min

Jupiter is striking in appearance (Figure 1), even through a small earth-based telescope. Its surface is covered with alternating bright and dark east-west bands. The dark clouds – called **belts** – are brownish red (photochemical products), **banded by lighter colored** cyclonic swirls and ovals resulting from Jupiter's fast rotation which causes severe coriolis. (The large diameter of Jupiter combined with its rotation period of less than ten hours moves its equator at 45,000 km/hr compared with 1,670 km/hr for the Earth.)

Alternating with the dark belts are bright yellow or tan **zones.** Jupiter's clouds are composed of ammonia, ammonium hydrosulfide, and water ice crystals. Telescopic spectra of Jupiter show that its atmosphere is composed of considerable amounts of hydrogen and helium as well.

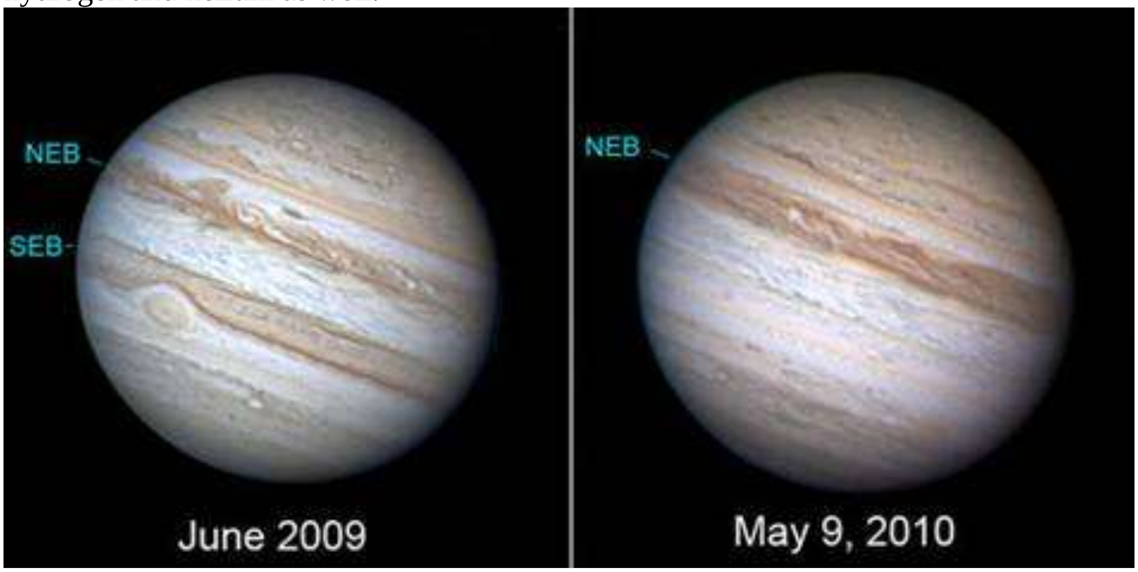


Figure 1. *Weather on Jupiter. Two images of Jupiter taken one year apart by amateur astronomer Anthony Wesley. Compare the cloud patterns on both images. How have they changed? From* *http://www.msnbc.msn.com/id/37132414/ns/technology_and_science-space/t/jupiter-lost-cloud-stripe-new-photos-reveal/#.UO2-FW9X2So*

Jupiter's banded appearance is caused by a combination of rotation and convection (Figure 2). Heat from Jupiter's warm interior powers deep convection currents which bring warm gas from the interior to the surface and allow cooler surface gases to sink below. The bright yellow zones represent warm rising material; the dark bands are cooler sinking gas. Cloud colors are caused by minor constituents, such organic molecules and compounds of sulfur and phosphorus. Because of the fast rotation of Jupiter the convection patterns have been stretched in an east-west direction.

WebVideo: Jupiter's Weather
http://www.bbc.co.uk/science/space/solarsystem/solar_system_highlights/atmosphere_of_jupiter#p006x535

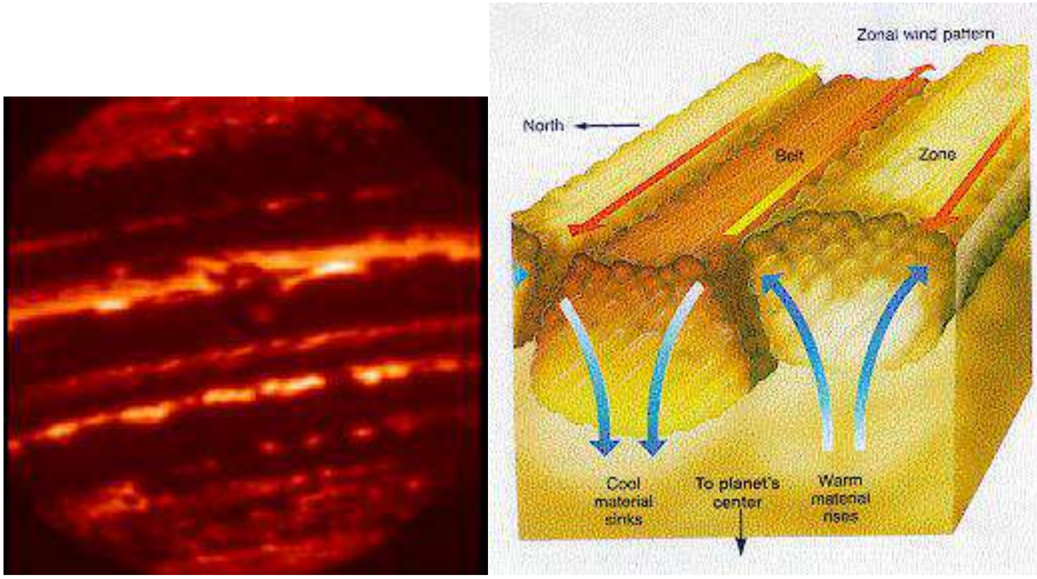


Figure 2. *Convection in the Jovian atmosphere. Left: Infrared emission from warm zones in Jupiter's atmosphere. Right: Schematic of Jovian convection, with warm cells (zones) of rising material and cooler belts of sinking material.*

In his book, *Cosmos*, Carl Sagan speculated that the conditions for life exist near the cloud tops in Jupiter's atmosphere. Although there is no solid surface there, the temperatures of 0-20° C, a pressure of 10 atmospheres, and abundance of water would be friendly to life. Floating microbes, perhaps parachute-shaped, could float indefinitely in the Jovian atmosphere, although updrafts to higher altitudes and a more hostile environment could kill them.

One of the most prominent features on the surface of Jupiter is the **Great Red Spot**, a remarkable oval surface feature approximately 26,000 by 14,000 kilometers in size, large enough to encompass two Earths (Figure 3). The Great Red Spot was first seen by the French-Italian astronomer Cassini with the aid of a telescope in 1665. Since it has been seen to shift in latitude, and presumably longitude, in the years subsequent to its discovery, it cannot be assumed to be associated with any underlying, permanent feature on Jupiter. Instead it is thought to be a powerful storm at least 300 years old. **What enables storms on Jupiter to have such a long life compared with those on the Earth?** This is not clear, but may result from Jupiter's enormous mass and coriolis force.

Measuring Jupiter's rotation is a problem because it has no visible solid surface. Measuring the rotation rates of the Great Red Spot, polar clouds, equatorial clouds, and the Jovian magnetic field all yield different values, although all are near 10 hours. Jupiter exhibits **differential rotation**, that is the rotation period is different at the equator and poles, with the equator taking 5 minutes longer to rotate once. The Great Red Spot sometimes rotates ahead of adjacent clouds and sometimes lags behind.

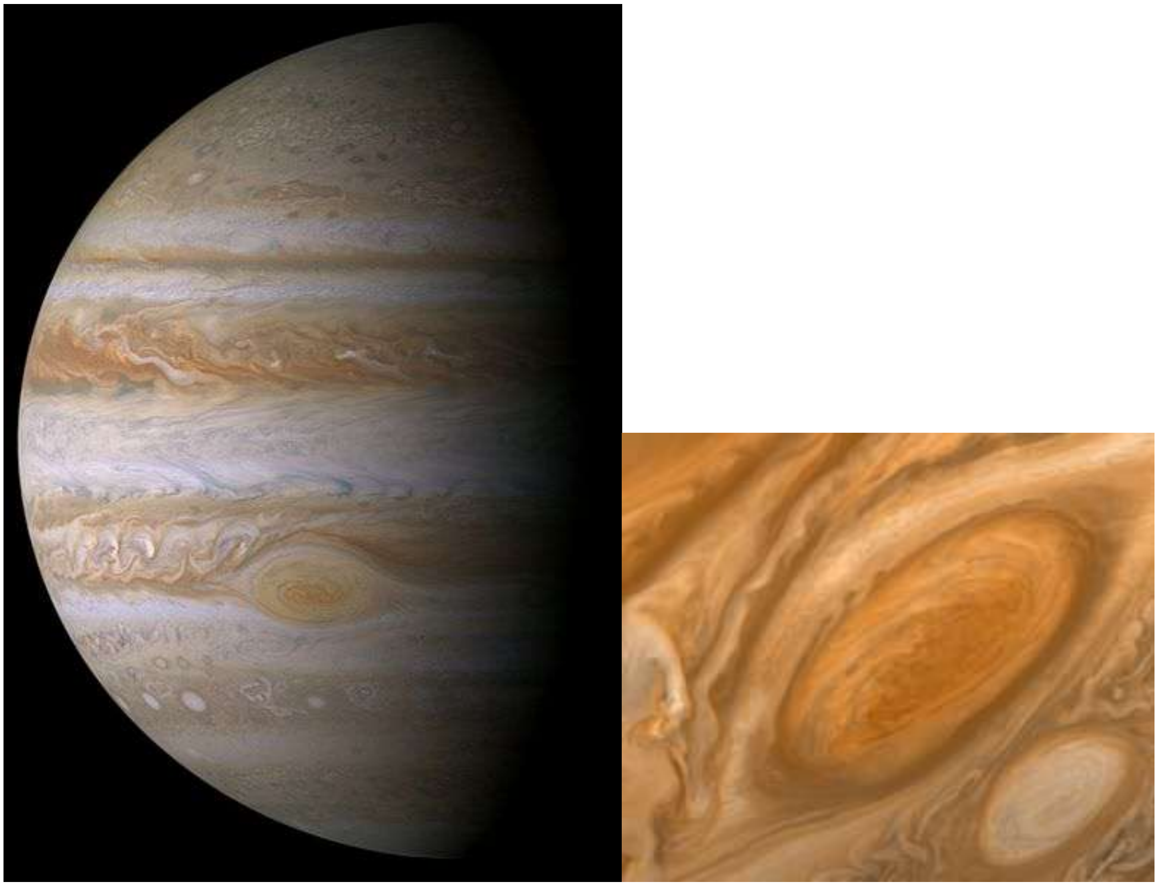


Figure 3. *Upper: The planet Jupiter with its prominent belts, zones, Great Red Spot and smaller white ovals. Below: a close-up of the Great Red Spot and a nearby white oval. NASA*

The physical state of Jupiter's interior can be inferred from its density of 1330 kg/m^3 and assuming that its composition is the same as the Sun – 86.1% molecular hydrogen (by number of molecules) and 13.8% helium (Figure 4). (As you will see in Chapter 12, it is thought that the Sun and planets condensed from the same cloud of gas and dust and that the Sun and gas giants should have nearly the same composition.) At 150 kilometers below the cloud tops the pressure is predicted to be 10 Earth atmospheres and hydrogen would be liquid.

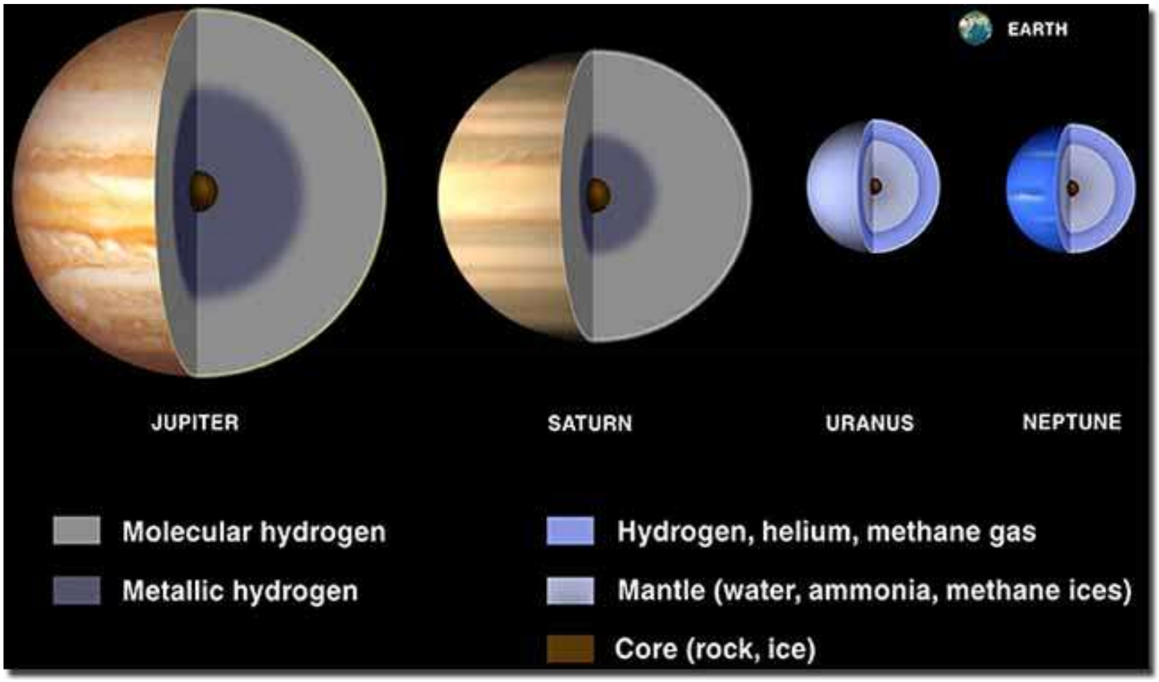


Figure 4. *Models of the interior structure of the outer planets. Jupiter is thought to have a mantle of liquid molecular hydrogen lying on top of electrically conductive or metallic hydrogen. The core is modeled with a core of 305 Earth masses of rock and iron.* **From llnl.gov**

Jupiter radiates strongly in the infrared putting out twice as much energy as it receives from the Sun. What is the source of this energy? It is thought that Jupiter is being powered by its own slow gravitational collapse.

Because of its high mass, at 20,000 kilometers depth the pressure should be 3 million atmospheres with a temperature of 11,000 K, resulting in a liquid metallic hydrogen core. Liquid hydrogen at this temperature is highly energetic and loses its electrons, which are free to conduct electricity. In this state hydrogen behaves as a metal. The result of this rotating, convecting, conductive fluid is a strong magnetic field. Indeed, Jupiter is observed to have a magnetic field some 19,000 times stronger than Earth's.

Using the expected composition in more refractory elements such as silicon, oxygen, and iron, Jupiter is expected to have a small rocky core, having about 4% of the Jovian mass, or 305 times the mass of Earth, squeezed by Jupiter's enormous mass into a sphere approximately 20,000 kilometers in diameter (compared to 12,756 km for Earth).

Since 1655, when Saturn was observed with a telescope by Christian Huygens, it has been known to have rings. Jupiter's rings, however, weren't discovered until 1977, the first direct proof that Saturn is not the only planet with rings (Figure 5). The Jovian ring system is too faint and close to Jupiter to be seen from Earth. The Voyager spacecraft took the first images of the Jovian ring system in 1977. The rings are composed of dark, tiny dust particles, probably of rocky composition. Since that time spacecraft have imaged ring systems around Uranus and Neptune as well.

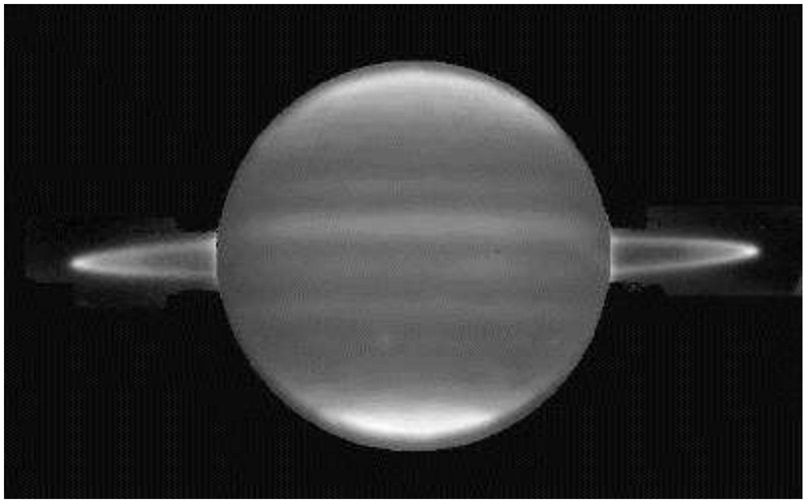


Figure 5. *Jupiter's rings. A Keck telescope image of Jupiter and its rings. From gps.caltech.edu*

Jupiter is accompanied by 16 satellites or moons (Figure 6), resembling a miniature solar system. The four largest of the Jovian satellites (Io, Europa, Ganymede, and Callisto) were discovered by Galileo in 1610, in one of the first astronomical discoveries made with the telescope (Figure 7).

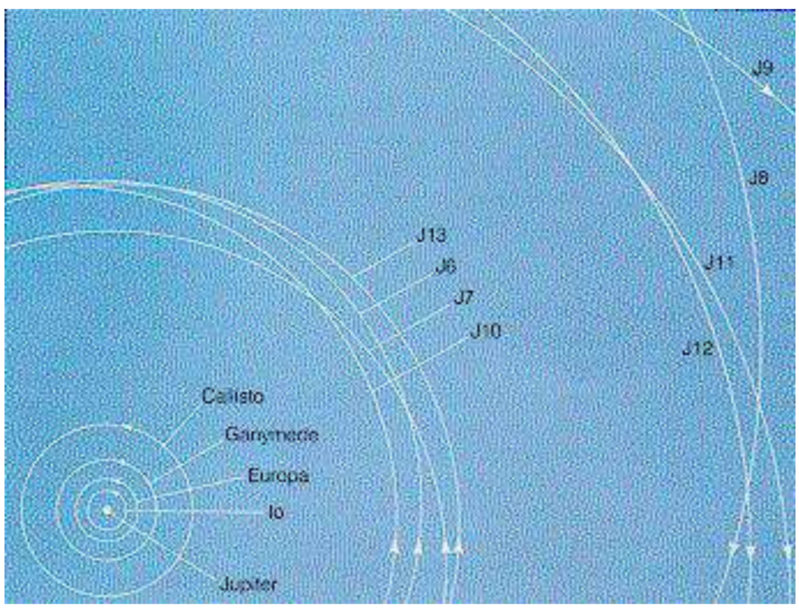


Figure 6. *The orbits of 12 of Jupiter's Moons. Some of Jupiter's outer satellites have highly elliptical orbits (e.g., the four outermost satellites shown here.*

Figure 7. *The Galilean Satellites: four largest satellites of Jupiter. Above, a telescopic image of Jupiter and her largest moons. Below they are shown individually in order of their distance from Jupiter: Io, Europa, Ganymede, and Callisto. (NASA).*

Table 10.2: *Bulk Properties of Jupiter's Satellites*

Moon	Distance from Jupiter (Jupiter radii)	Size (km)	Orbital Period (Earth days)	Mass (lunar masses)	Density (kg/m^3)
Metis	1.79	40	0.29		
Adastea	1.81	20	0.30		
Amalthea	2.54	200	0.50		
Thebe	3.11	90	0.67		
Io	5.91	3630	1.77	1.22	3600
Europa	9.40	3140	3.55	0.65	3000
Ganymede	15.0	5260	7.16	2.02	1900
Callisto	26.4	4800	16.7	1.47	1900
Leda	155	15	239		
Himalia	161	180	251		
Lysithea	164	40	259		
Elara	164	80	260		
Ananke	297	30	631 (retrograde)		
Carme	317	40	692 (retrograde)		
Pasiphae	329	70	735 (retrograde)		
Sinope	332	40	758 (retrograde)		

A. Io

Io is the innermost of the four Galilean satellites of Jupiter. It orbits Jupiter with a period of 1.8 days with the same side facing Jupiter (synchronous rotation). On the close approach of Voyager 1 to Jupiter, 8 giant active volcanoes were discovered and named after legendary gods and goddesses associated with fire. The most active volcano is Loki. Io's strikingly colored surface is a palette formed from volcanic activity. Black dots mark volcanic vents. Lava flows from more than 400 active volcanoes paint the surface shades of yellow and red with sulfur and sulfur dioxide. Some of Io's mountain peaks, formed by crustal motion and uplifting, reach heights greater than that of Mount Everest. Io is the most volcanically active body in the Solar System. Io's synchronous rotation and volcanic activity are the result of tidal interaction with Jupiter. Tidal forces on Io from Jupiter and its other moons periodically squeeze Io like we would squeeze a rubber ball. This produces tidal heating of Io's interior, keeping it molten throughout. Sulfur and sulfur dioxide cover Io's surface. Sulfur changes color with temperature. Pure hot sulfur is black and as it cools it becomes red, then yellow. The temperature of sulfuric lava on the surface, if not contaminated, can be roughly determined from its color. The portion of the surface that is white is sulfur dioxide that snows on the surface of Io (much like volcanoes on Earth that emit sulfur dioxide).

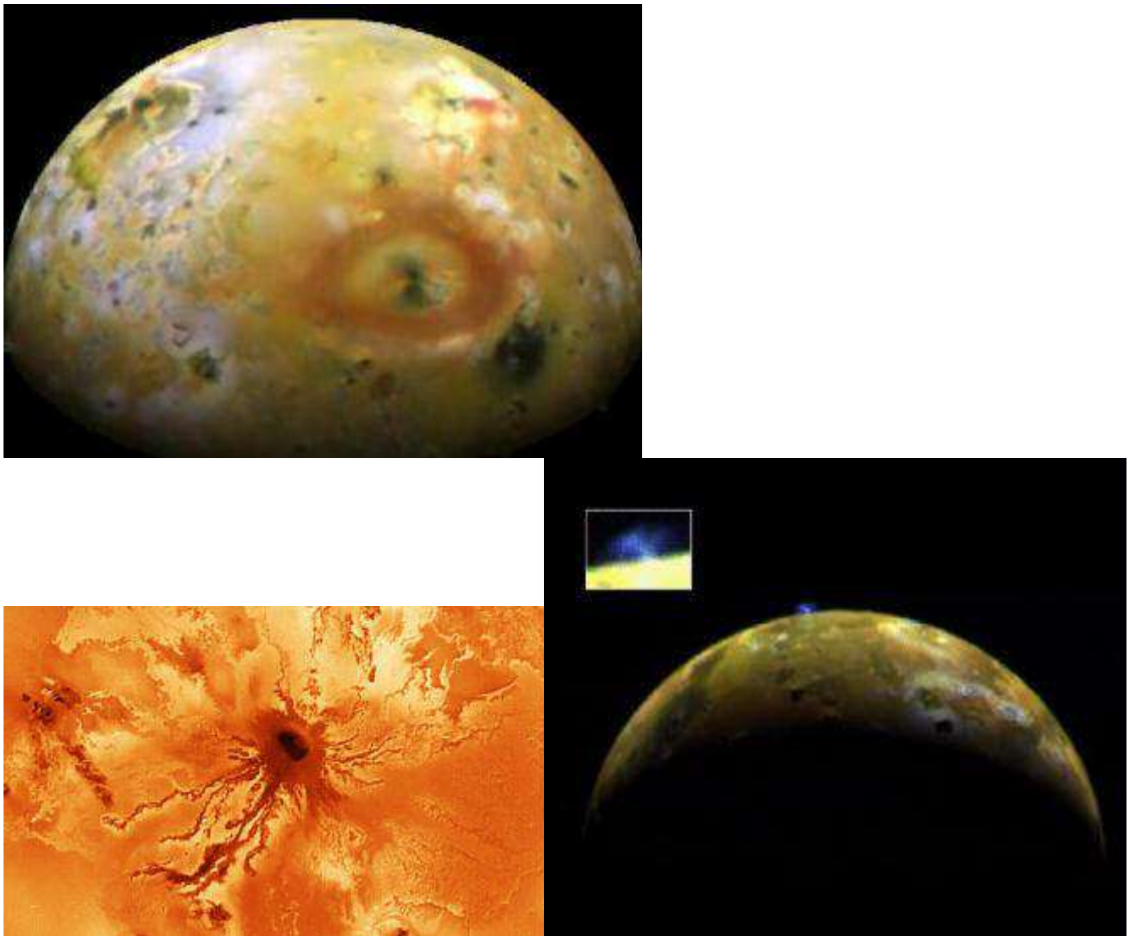


Figure 8. *An Io montage.* ***Upper Panel.*** *A Voyager image of the Jovian satellite Io. Io's pizza-like appearance is due to a surface covered with sulfur and sulfur dioxide frost.* ***Lower Left.*** *Ra Patera, one of Io's active volcanoes. This Voyager image shows the hot black sulfur at the volcano's vent, and red sulfur flows up to 400 km long.* ***Lower Right.*** *An eruption from Io's Ra Patera shield volcano was imaged by the Galileo spacecraft. A plume of sulfur dioxide frost condensing up to 150 km above the surface of Io.* ***NASA***

B. Europa

The second innermost of the Galilean satellites is Europa (Figure 9). Europa was first imaged in detail by the Voyager 2 spacecraft. Europa orbits Jupiter every 3.5 days, with synchronous rotation. It has a smooth surface with no mountains and few craters but a network of streaks and cracks. Its appearance and low density, 2979 kg/m^3, can be explained by an outer shell of ice, perhaps 100 km deep, covering the underlying terrain. Tidal flexing of Europa, similar to what takes place with Io, has produced cracks in this icy crust. Water has apparently flowed up through these cracks and frozen in them, producing streaks on the surface. The lack of craters can be explained by tides causing a continual repaving of surface in this manner.

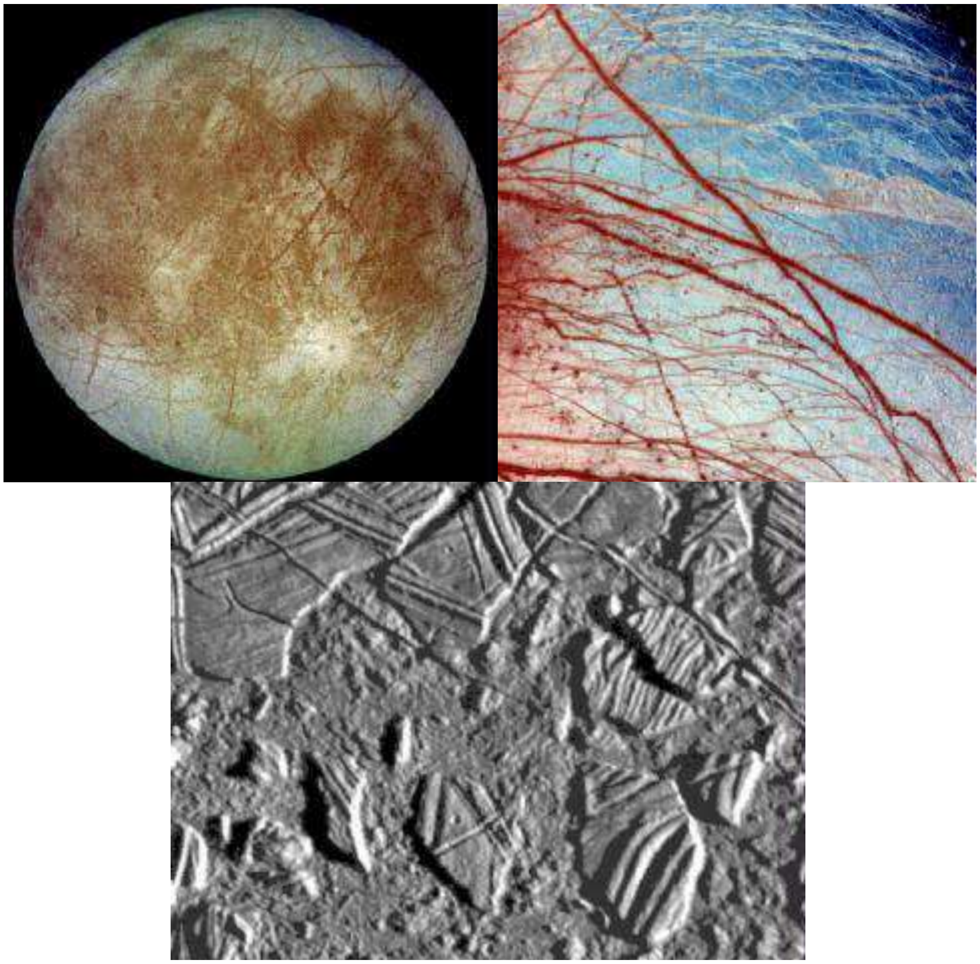


Figure 9. *Jupiter's satellite Europa imaged by the Galileo spacecraft orbiting Jupiter***.** **Upper Left.** *Europa's surface is covered by cracked and dirty, brownish ice, floating on oceans of water. Europa is the only other body in the Solar System, other than the Earth, thought to be covered by oceans of liquid water.* **Upper Right.** *A close-up, false-color coded image of Europa's cracked and mottled surface.* **Lower.** *Icebergs floating on Europa's water ocean.* **NASA.**

C. Ganymede

Ganymede is the third of the Galilean satellites and the largest satellite in the Solar System with a diameter greater than Mercury's, but a much lower density of 1940 kg/m^3 (Figure 10). Like Europa, Ganymede appears to have a thick crust of ice. Like our Moon, Ganymede is covered by two types of regions, cratered and smooth. Dark polygon-shaped regions are sprinkled with numerous craters. Between the cratered regions are lighter and uncratered, grooved terrain. The lack of craters indicates that the grooved terrain is much younger than the cratered surface. Grooves are ridges 1 kilometer high, spaced 10 to 15 kilometers apart, possibly caused by plate tectonics in the distant past, which stopped when the crust froze. Water apparently seeped up through tectonic cracks and froze on the surface, analogous to what occurred on the Moon when the maria formed.

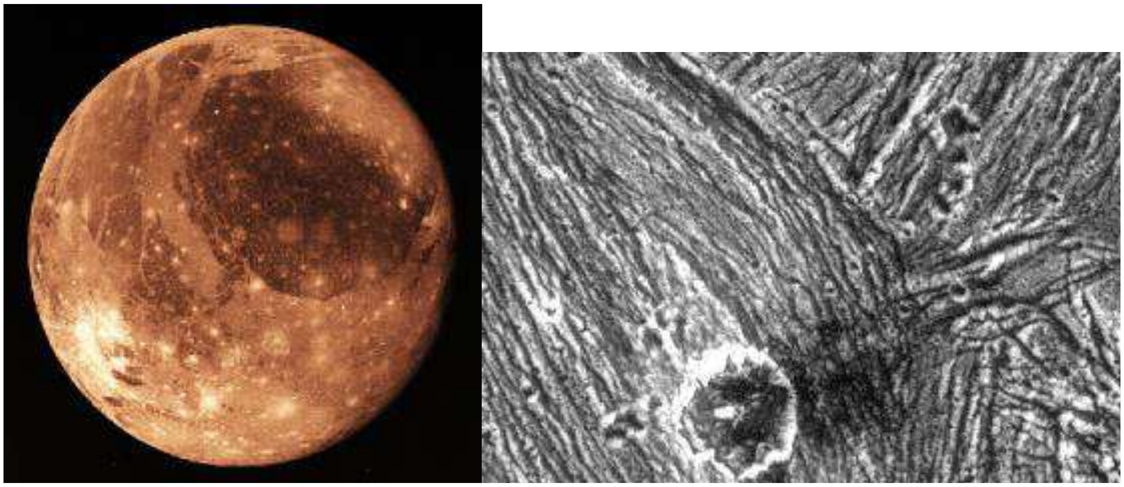


Figure 10. Left Panel. *Ganymede, Jupiter's largest satellite is covered with a layer of dirty ice.* **Right Panel.** *Ganymede has a cracked and grooved surface thought to be produced by plate tectonics. An impact crater can be seen at the bottom of this image.* **NASA.**

D. Callisto

Callisto is the outermost Galilean satellite with a synchronous orbital period of 16.7 days (Figure 11). Callisto is nearly Ganymede's twin, with 91% of its diameter and 96% of its density, along with similar surface features. Callisto does not have Ganymede's grooved terrain, only numerous impact craters are seen covering an icy crust. The absence of grooved terrain is possibly a result of less active plate tectonic on Callisto or an interior that froze more quickly than Ganymede's. In any case Callisto is farther away from Jupiter and has less tidal stress and heating than does Ganymede.

Voyager imaged a huge impact structure on Callisto, named the Valhalla Basin. It is surrounded by rippled surface from the impact that presumably melted the surface. The resulting cracks in the surface froze into place. These rings extend out to a radius of 3000 km.

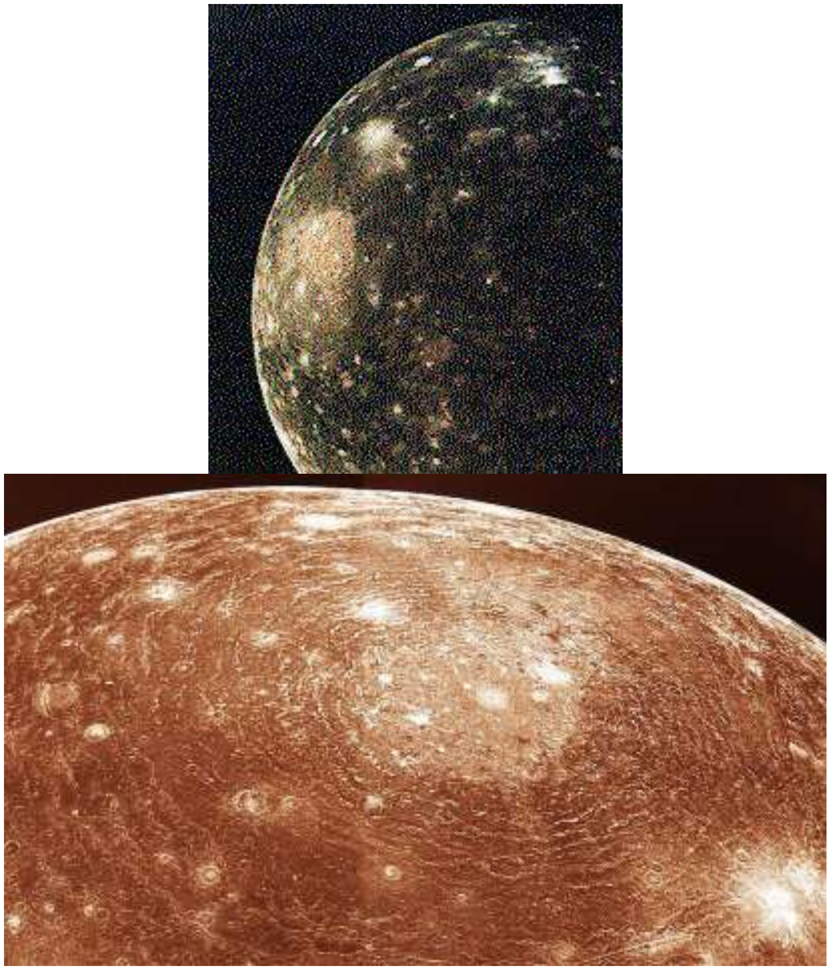


Figure 11. *Callisto is the most heavily cratered of Jupiter's ice-covered Galilean satellites. Seen on the lower panel is a multi-ring impact structure, Valhalla, which is about 3800 km in diameter. NASA*

E. Other Jovian Moons

In addition to the Galilean satellites, Jupiter is orbited by twelve other moons and a faint ring of tiny rock fragments (Figures 5 & 6). The rings are composed of three ringlets extending from Jupiter's cloud tops to an altitude of 50,000 kilometers.

III. Saturn

Saturn is the only planet in the Solar System will rings that can be seen directly through Earth-based telescopes (Figure 12). Like Jupiter, it has a thick atmosphere with east-west belts and zones. Saturn's atmosphere is hazy with less contrast between belts and zones than is seen on Jupiter. Saturn has differential rotation: varying from 10 hours 14 minutes at the equator to 10 hours 40 minutes at high latitudes.

Table 10.3: *Bulk Properties of Saturn*

Property	Measurement
Mass	95.2 M_{Earth}
Radius	60,270 km
	9.45 R_{Earth}
Average Density	690 kg/m^3
Average Distance from the Sun	9.53 AU
Orbital Period - Sidereal	29.5 Earth years
Orbital Eccentricity	0.056
Rotational Period – Sidereal (Equatorial)	10 h 14 min

Webnote: Saturn's Rotation
http://science.discovery.com/tv-shows/wonders-with-brian-cox/videos/wonders-of-the-solar-system-the-planet-saturn.htm

Saturn has the lowest density of any planet in the solar system, 690 km/m^3, less than that of water. This low density implies an interior similar in structure to Jupiter's: molecular hydrogen around a mantle of metallic hydrogen and a solid rocky core.

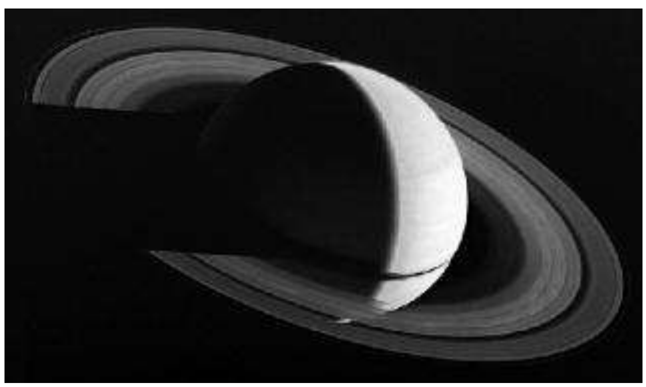


Figure 12. *Saturn, casting its shadow across its rings. (NASA)*

Farther away from the Sun, the Saturnian atmosphere is colder than Jupiter's. As a result, ammonia is frozen solid deeper into the atmosphere and methane ice is more prominent.

Saturn's ring system, 274,000 kilometers (171,000 miles) in diameter and about 100 meters thick are Saturn's trademark, seen even through a small telescope (Figure 13). Saturn's rings were first seen by Galileo in 1610 when he viewed Saturn through the telescope. The Dutch astronomer Christian Huygens was the first to realize that a flat ring encircled Saturn when he telescopically observed the planet in 1659. Saturn's rings are more prominent and complex than Jupiter's. The rings are made of rock to boulder sized blocks of ice. The ring system is divided into bright and dark rings separated by gaps where ring particles have the lowest density. The widest gap is Cassini's division, named after their discoverer. Even the broad rings separate into thousands of narrow, high-contrast ringlets. Additional structure, seen only in high-resolution spacecraft imagery, includes wavy edges, twisting, and radial spokes.

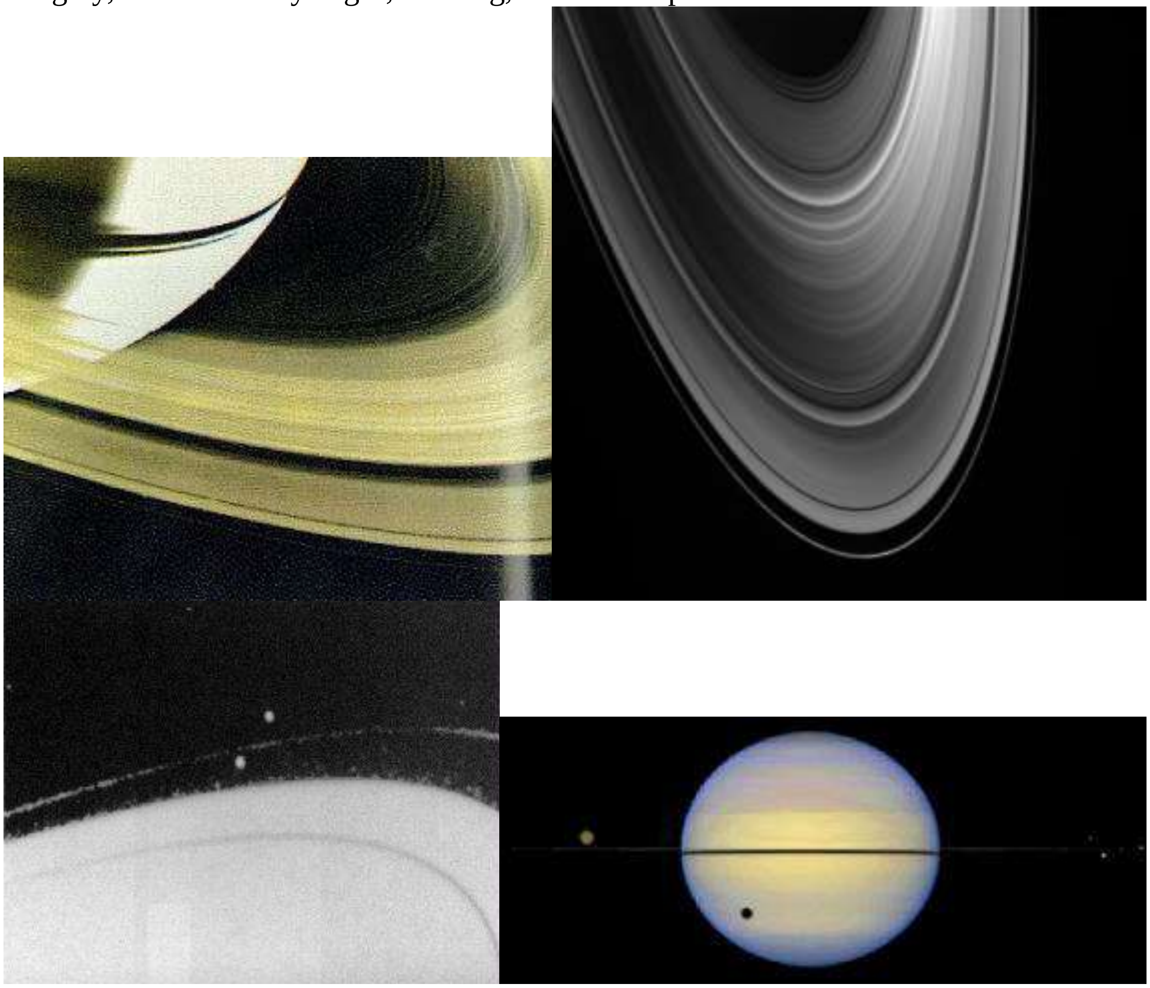


Figure 13. *Saturn's rings.* **Upper Left.** *A Voyager 1 image of Saturn and its rings of orbiting chunks of ice and rock. The shadows produced by the rings can be seen as a dark belt across the Saturn's bright disk.* **NASA. P 238-13.35. Upper Right.** *A Voyager close-up of Saturn's rings showing the complexity of its gaps. Color differences reflect the different compositions of the ring particles***. NASA Lower Left.** *A Voyager spacecraft image of* t*wo of Saturn's tiny, innermost satellites, Prometheus and Pandora, are so-called shepherd satellites, using their gravitational influence to herd disk particles into a narrow ring between the two***. NASA Lower Right.** *An image of Saturn's rings seen edge-on by the Hubble Space Telescope. Saturn's largest satellite Titan can be seen on the left, as well as its shadow on the lower part of Saturn's disk. Four other moons of Saturn can be seen just above the ring plane: Mimas, Tethys, Janus, and Enceladus.* **NASA**

What causes the formation of planetary ring systems? At distances between two and three planetary diameters from the mother planet, tidal forces are large enough to pull a moon or moonlet apart. The ring systems of all four gas giants are inside this distance.

Tidal forces keep ring particles from gravitationally accumulating, gravity and angular momentum (spin) keep the particles collapsed into a disk. Rings could have been formed by the destruction of a Saturnian moon. Eventually all of the ring material will fall into Saturn, similar to satellites orbiting the Earth, which eventually crash to the Earth's surface.

What causes the intricate ring structure, including gaps and spokes? Gravitational forces from moons and moonlets embedded in the rings are the source of intricate ring structure. Voyager 1 discovered two 200-km moonlets on either side of Saturn's F ring, for example. Moons like this are called **shepherd satellites**. Particles in Cassini's division orbit with half the period of the nearest moon, Mimas. Any particles in the gap would be pulled out of the division every two orbits.

Seventeen satellites orbit Saturn; all are low in density, 1000 to 2000 kg/m^3 and rich in methane, ammonia and water ices (Figure 14). Saturn's satellites are less geologically varied than Jupiter's. They are less dense, icier, and brighter, perhaps because Saturn is farther from Sun. Saturn's satellites can be placed into four groups, in order of their distance from Saturn: the small innermost satellites near Saturn's rings, the larger Saturnian satellites, the giant moon Titan, and the satellites outside Titan's orbit.

Table 10.4: *Bulk Properties of Saturn's Satellites*

Moon	Distance from Saturn (Saturn radii)	Size (km)	Orbital Period (Earth days)	Mass (lunar masses)	Density (kg/m^3)
Pan	2.23	20	0.58	4×10^{-8}	
Atlas	2.30	40	0.60		
Prometheus	2.32	80	0.61		
Pandora	2.37	100	0.63		
Janus	2.52	190	0.69		
Epimetheus	2.52	120	0.69		
Mimas	3.10	394	0.94	5.4×10^{-4}	1200
Enceladus	3.97	502	1.37	1.1×10^{-3}	1200
Tethys	4.92	1050	1.89	1.0×10^{-2}	1300
Telesto	4.92	25	1.89		
Calypso	4.92	25	1.89		
Dione	6.28	1120	2.74	1.5×10^{-2}	1400
Helene	6.28	30	2.74		
Rhea	8.78	1530	4.52	3.4×10^{-2}	1300
Titan	20.3	5150	16.0	1.83	1900
Hyperion	24.7	270	21.3		
Iapetus	59.3	1440	79.3	2.6×10^{-3}	1200
Phoebe	217	220	550 (retrograde)		

The largest inner Moon, Janus, is about 200 km in diameter, irregularly shaped, and thought to be almost purely ice. These are perhaps fragments of shattered moons having larger orbital distance.

Mimas, Enceladus, Tethys, Dione, and Rhea can be seen telescopically from the Earth. All are nearly spherical and have synchronous rotation (Figure 14). They vary in size from 300 to 1500 kilometers in diameter. These satellites are bright with low densities, only 20% to 40% greater than ice, indicating that they are mostly ice. All have evidence of fractures indicating crustal evolution (expansion) subsequent to internal heating. Enceladus is the one experiencing the most recent geological activity with cratered highlands as well as icy maria. The maria are regions where water has erupted onto the surface covering areas with ice which subsequently underwent only light cratering.

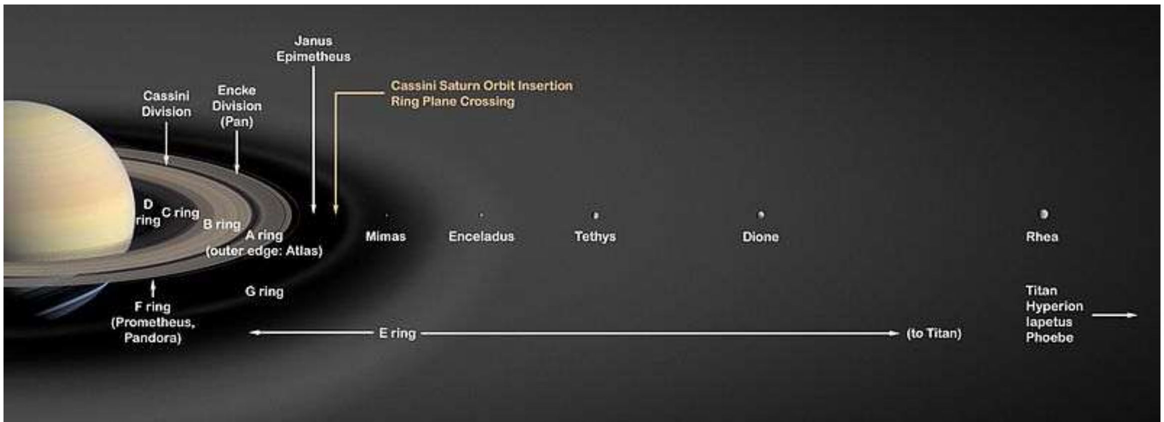


Figure 14. *A scale drawing of Saturn and its largest moons.*

Titan, at 5,150 kilometers diameter, is the second largest moon in the Solar System and larger than the planet Mercury (Figure 15). Titan is the only satellite in our Solar System with a substantial atmosphere. In 1944, telescopic spectra showed that Titan has an atmosphere with 1.6 times the pressure of Earth's atmosphere and a high abundance of methane. It has since been discovered that the atmosphere contains reddish smog, produced by reactions between methane and sunlight, similar to the smog produced over large metropolitan areas on the Earth. Approximately 90% of the atmosphere is nitrogen. In addition, there are traces of organic molecules like ethane, acetylene, ethylene, and hydrogen. At its low temperature, methane and ethane can exist as a solid, liquid, and gas. It is possible for Titan to have methane snow or rain and ethane lakes. The current atmosphere of Titan is thought to be similar to Earth's primitive atmosphere. The existence of simple organic molecules on Titan may have implications for the evolution of life on our own planet, which will be discussed later.

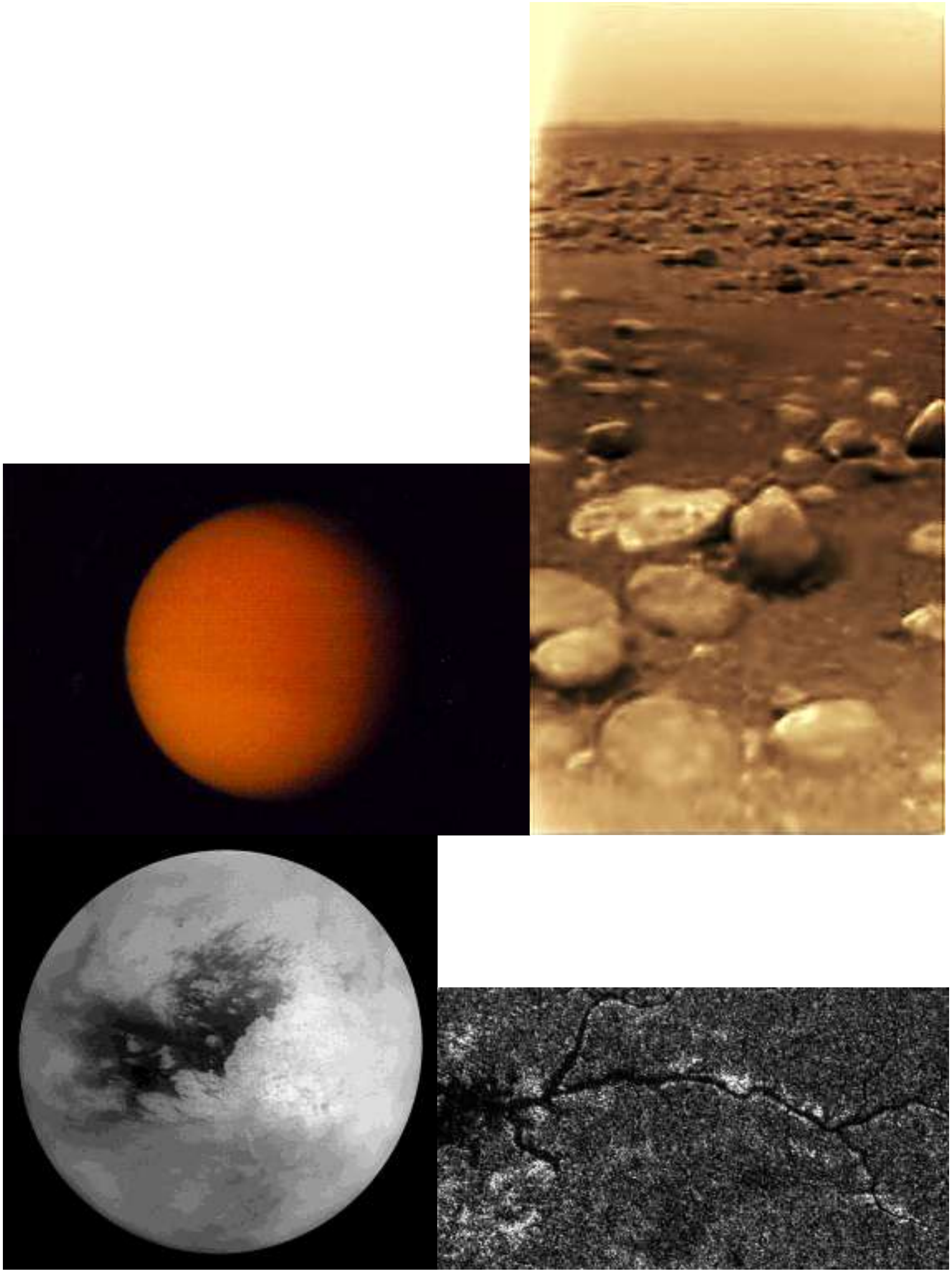


Figure 15. *Saturn's largest moon Titan. The only planetary satellite with a dense atmosphere and the only solar system body with liquid on the surface, other than the Earth.* ***Upper Left and Lower Left.*** *Images of Titan from the Cassini mission in 2005.* ***Upper Right.*** *The only image of Titan from its surface taken by the European Space*

Agency Huygens probe in 2005. ***Lower Right.*** *Lakes of methane found by the Cassini spacecraft.* ***(NASA).***

Titan has synchronous rotation and orbital periods. Although its surface temperature is only 93 K (-292° F?), its temperature is as high as it is only because of the relatively strong greenhouse effect provided by Titan's atmosphere. Because of this low surface temperature, methane can exist on the planet in gas, liquid, and solid phases, raining or snowing onto the surface and producing oceans of methane and ethane.

Saturn has three irregularly shaped outer moons, Hyperion, Iapetus, and Phoebe ~~(Figure 17).~~ Iapetus is unique in that is sports one dark hemisphere, the one leading the moon in its orbit, and a white trailing hemisphere. It is thought that the dark side is produced as Iapetus collides with dark dust and sweeps it up as it orbits Saturn. The dust is most likely from the outermost dark satellite Phoebe, spiraling into Saturn after being knocked off the surface by meteorite impact.

IV. Uranus

In the first discovery of a new planet since ancient times, the English astronomer William Herschel first saw Uranus in 1781 while star mapping. Uranus is too far from the Sun for astronomers to use Earth-based telescopes to resolve surface markings.

Table 10.5: *Bulk Properties of Uranus*

Property	Measurement
Mass	14.5 M_{Earth}
Radius (Equatorial)	25,559 km 4.01 R_{Earth}
Average Density	1290 kg/m^3
Average Distance from the Sun	0.387 AU
Orbital Period - Sidereal	84.0 Earth years
Orbital Eccentricity	0.047
Sidereal Rotational Period (Equatorial)	16 h 30 min (retrograde)

Uranus' rotational axis is tipped over by 98° to its orbital path, producing dramatic seasons. Each pole is pointed alternately toward and away from the Sun with a period equal to the 84-year orbital period of Uranus. This gives each hemisphere a twenty-year winter without sunrise and a twenty-year summer with no sunset. Uranus has a 23-hour rotational period. From a point on the daylight side of Uranus, the sun appears to circle overhead with a 23-hour period.

When Voyager 2 reached Uranus it discovered a greenish blue planet, with a layer of haze partially obscuring an almost featureless layer of clouds (Figure 16). Uranus has an atmosphere of *hydrogen* and helium, like those of Jupiter and Saturn, but colder, owing to its distance from the Sun. So far from the Sun, and lacking a central heat source causes a lack of the convectively driven storm system such as those seen on Jupiter and Saturn (and the Earth). The result is a relatively featureless atmosphere.

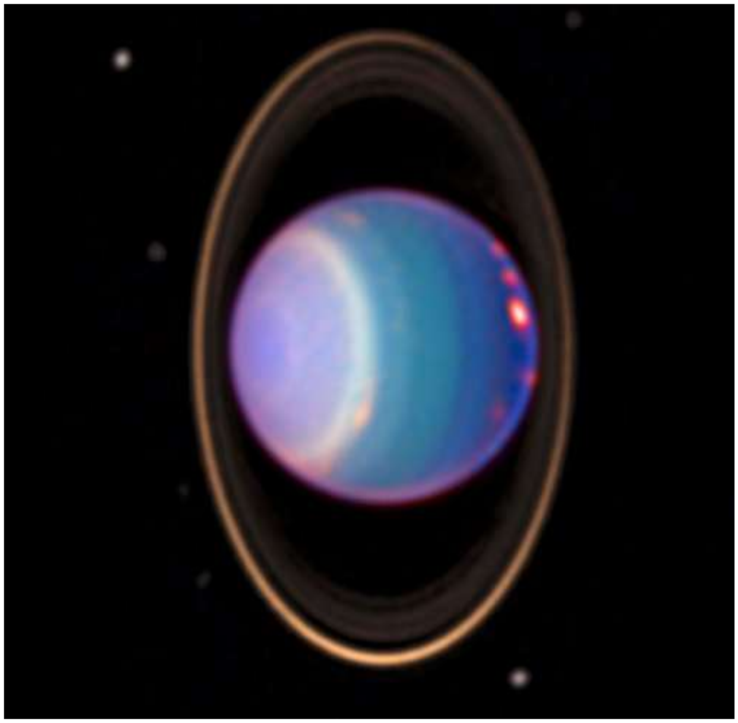


Figure 16. *The Uranian ring system. These Hubble Space Telescope images of Uranus in the infrared has been computer enhanced and false-colored to show the faint, narrow rings of Uranus. It also enhances the structure in Uranus' atmosphere.* **NASA.**

Models of Neptune and Uranus show no metallic hydrogen mantles, because the pressure of these planets isn't high enough. Instead there are unseen oceans of methane and water surrounding a rocky core.

Although a Uranian ring system cannot be directly seen from Earth, a ring system was discovered in 1977, when a star passing through Uranus blinked off and on at some distance from the planet as it passed behind particles forming 9 narrow rings (Figure 16). These rings are probably kept tight by unseen shepherd satellites. Voyager 2 subsequently found two such shepherd satellites bracketing the thickest ring. Later Voyager 2 found rings around Neptune, not complete circular rings but arcs, narrow like Uranian rings, with the addition of faint broad rings like those of Jupiter.

Uranus has 15 satellites, five of which can be seen with the aid of a telescope (Figure 17). Uranus has 10 small moons, 30 to 110 km in diameter, discovered by Voyager 2. The latter are dark and probably composed of carbon-rich clays, similar to many meteorites (Chapter 11).

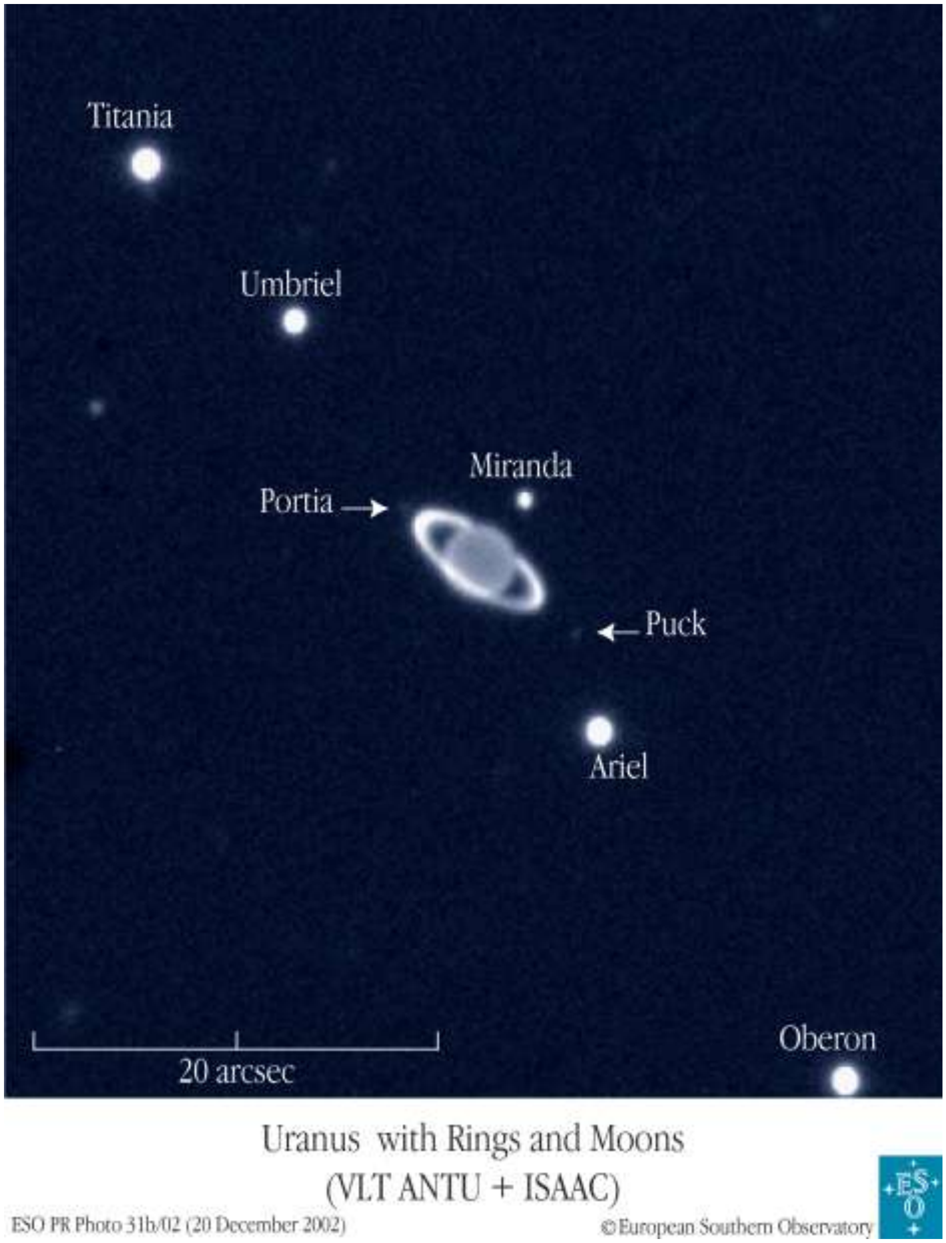


Figure 17. *The planet Uranus with its rings and moons from a ground-based telescope image from the European Southern Observatory (Chile).*

Table 10.6: *Bulk Properties of Uranus' Satellites*

Moon	Distance from Uranus (Uranus radii)	Size (km)	Orbital Period (Earth days)	Mass (lunar masses)	Density (kg/m^3)
Cordelia	1.95	40	0.34		
Ophelia	2.11	50	0.38		
Bianca	2.32	50	0.44		
Cressida	2.42	60	0.46		
Desdemona	2.45	60	0.48		
Juliet	2.53	80	0.50		
Portia	2.59	80	0.51		
Rosalind	2.74	60	0.56		
Belinda	2.95	60	0.63		
Puck	3.37	170	0.76		
Miranda	5.09	485	1.41	1.1×10^{-3}	1300
Ariel	7.48	1160	2.52	1.8×10^{-2}	1600
Umbriel	10.4	1190	4.14	1.8×10^{-2}	1400
Titania	17.1	1610	8.71	4.8×10^{-2}	1600
Oberon	22.8	1550	13.5	4.0×10^{-2}	1500

Miranda is the innermost of the five largest satellites, and is only 470 km in diameter (Figure 18). It shows evidence of much geological activity including a network of fractures and grooves. Although such a small satellite is not expected to show significant geological activity, one of its unique surface features is a cliff 5 kilometers in height, or 1% of the diameter of Miranda. (In comparison, a cliff on the Earth that is 1% of the Earth's diameter would be 120 kilometers high.) It is not known where the energy driving this geological activity comes from, whether it is impact in origin or from the tidal interaction with other moons.

The other four large moons of Uranus are about 1/3 the size of our Moon, with the cratering of surfaces billions of years old. But several show evidence of additional geological activity, including linear surface fractures. Like Miranda, the energy source powering this geological activity is unaccounted for.

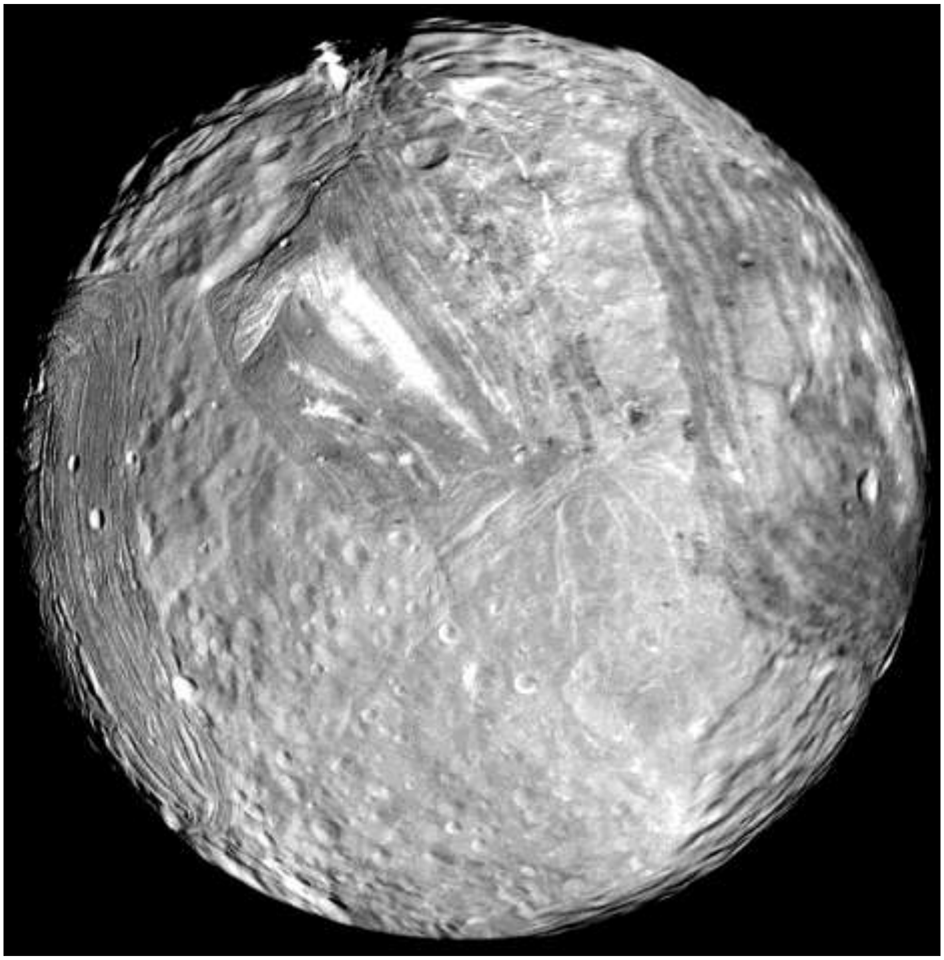


Figure 18. *The Uranian moon Miranda. The only high-resolutions made of Miranda were made by the Voyager 2 flyby in 1986. The surface is stongly marked by tidally-induced faults as well as volcanic activity from icy magma.* ***(NASA)***

V. Neptune

English astronomer J.C. Adams and the French astronomer Urbain Leverrier predicted the position of Neptune from slight observed deviations in the orbit of Uranus from a purely elliptical orbit. Adams had difficulty interesting astronomers in searching for a planet at his predicted position. Leverrier successfully persuaded two German astronomers to help in the discovery. They found the planet within one half hour of starting their search in 1846. Since its discovery, Neptune has completed less than one 164-year orbit of the Sun.

Table 10.7: *Bulk Properties of Neptune*

Property	Measurement
Mass	17.1 M_{Earth}
Radius	24,764 km 3.88 R_{Earth}
Average Density	1640 kg/m^3
Average Distance from the Sun	30.1 AU
Orbital Period - Sidereal	164.8 Earth years
Orbital Eccentricity	0.009
Sidereal Rotational Period	16 h 7 min

Neptune has an ocean-blue methane-rich atmosphere with no zones or belts (Figure 19). Neptune, unlike Uranus, does have some distinctive cloud features including dark bands, and a large oval storm system called the Great Dark Spot, similar to Jupiter's Great Red Spot**.** The Southern Hemisphere Great Dark Spot disappeared in 1994 but was replaced by a similar spot in the Northern Hemisphere for reasons that are not understood**. Why is there such a difference in appearance between Neptune and Uranus?** Neptune has a mysterious energy source, radiating away 2.7 times the solar energy incident on the planet. The result is that the atmospheric temperature of Neptune is actually greater than that of Uranus (even though Neptune is farther from the Sun). Clouds, which form in the warmer layers of the atmosphere, are seen at higher altitudes in Neptune than in Uranus, above the haze layer where they can easily be seen. The blue coloration seen in the atmospheres of Uranus and Neptune are produced by relatively high abundances of methane, compared with Jupiter and Saturn.

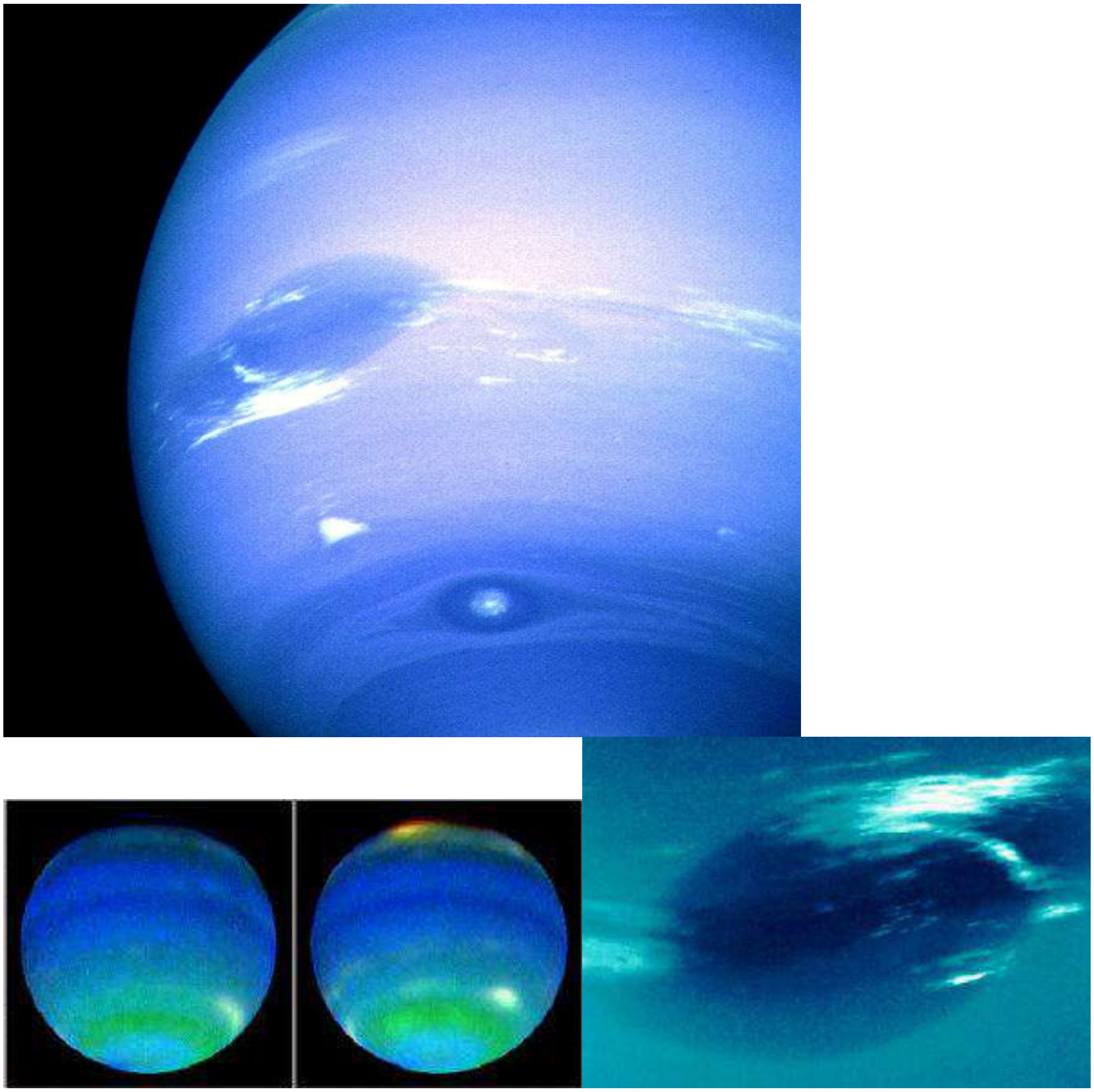


Figure 19. *Neptune's atmosphere.* **Panel A.** *Time-lapse images of Neptune. These images show the changing cloud patterns in Neptune's atmosphere. The blue color is due to methane which absorbs preferentially absorbs red sunlight entering the atmosphere. Yellow patches are clouds in the upper atmosphere.* **NASA Panel B.** *A Voyager 2 image of Neptune's Great Dark Spot, similar in size and southerly latitude to Jupiter's Great Red Spot. Both spots are thought to be enormous and long-lasting storm systems. The Great Dark Spot disappeared in 1994, only to be replaced by another dark spot appearing in the northern hemisphere.* **NASA. P 261-15.7.**

Neptune harbors 2 moons that were discovered by telescope (Figure 20). Voyager discovered 5 more on its passage by Neptune in 1989. As with the other gas giants, the small moons are just outside the edge of a ring system. The inner four moonlets are 30 to 120 km in diameter. The fifth, Proteus is 400 km in diameter. It is very dark with a large impact crater, and similar to many of the moons of the Solar System, it has a crater large enough to have been produced by an impact just short of the energy that would have completely shattered the satellite.

Figure 20. *Neptune and Neptune's moons.*

Table 10.6: *Bulk Properties of Neptune's Satellites*

Moon	Distance from Neptune (Neptune radii)	Size (km)	Orbital Period (Earth days)	Mass (lunar masses)	Density (kg/m^3)
Naiad	1.94	60	0.30		
Thalassic	2.02	80	0.31		
Designate	2.12	180	0.33		
Galatea	2.50	150	0.43		
Larissa	2.97	190	0.55		
Proteus	4.76	415	1.12		
Triton	14.3	2760	5.88 (retrograde)	0.291	2100
Nereid	223	200	360.2	3.4×10^{-6}	2000

Triton, at 5,400 kilometers diameter, is Neptune's largest moon and the 7th largest satellite in Solar System (only a little smaller than our Moon). Triton is a creamy-white moon with few impact craters (indicating a relatively young surface) and a sparse atmosphere, mostly nitrogen with some methane (like Titan's atmosphere, but thinner). The atmospheric pressure on Triton is 0.001% of the Earth's, resulting in negligible surface erosion. However, Triton's atmosphere contains thin clouds and a layer of haze 5 to 10 kilometers in altitude. Because of the high inclination of Triton's pole and the 165-year period of Neptune, Triton experiences a 41 year long winter. As a result, it is cold enough in winter darkness for solid nitrogen and possibly solid methane to exist at the poles. With a surface temperature of 38 K (-391° F), Triton has the coldest surface imaged by spacecraft to date. It is thought that Triton's surface is covered by methane and nitrogen ices contaminated by darker silicates.

Voyager 2 saw active volcanic eruptions on Triton, with plumes towering 8 kilometers above the surface, and then carried horizontally by winds aloft. Eruptions are originating from an uncratered surface. **What kinds of eruptions are being seen? How are they caused? What is the ultimate source of heat driving the eruptions?** The answers to these questions are not known.

Triton has a large inclination to Neptune's equator, and an orbital motion that is retrograde motion compared to all of the other moons. The reasons for these are unclear. Perhaps large tidal forces are causing it to spiral into Neptune.

The outermost moon of Neptune is Nereid, held in a very elliptical orbit near edge of Neptune's gravitational influence. Orbits of Triton and Nereid suggest they did not form with their current orbits but are either captured or the orbits were modified by the close encounter of another body. It can be generalized that collisions and captures influenced many of the planets and their satellites.

VI. Pluto

Although Pluto has a solid surface, it is unlike any of the terrestrial planets: it has a highly elliptical orbit (sometimes taking it inside the orbit of Neptune) which is inclined by 17° to the ecliptic and a density of only 1800 kg/m^3, less than half of that of the terrestrial planets.

Table 10.5: *Bulk Properties of Pluto*

Property	Measurement
Mass	0.002 M_{Earth}
Radius	1190 km 0.19 R_{Earth}
Average Density	1800 kg/m^3
Average Distance from the Sun	39.5 AU
Orbital Period - Sidereal	248.6 Earth years
Orbital Eccentricity	0.249
Sidereal Rotational Period	6.39 Earth days (retrograde)

Pluto was discovered in 1930, by American astronomer Clyde Tombaugh at Lowell Observatory. Tombaugh's search was motivated by perceived deviations of Neptune's orbit from a perfectly elliptical orbit (Figure 21). However it is now thought that real deviations to Neptune's orbit were too small to be seen and that it was really an accidental discovery. It is also somewhat problematic whether or not Pluto is really a planet. At 2300 kilometers diameter it is smaller than any other planet and seven moons. It is the only solid-surfaced planet in the outer solar system. It has the most elliptical and inclined orbit of any planet in our Solar System, occasionally coming closer to the Sun than Neptune does. It has been proposed that Pluto is an escaped satellite of Neptune or a large icy planetesimal.

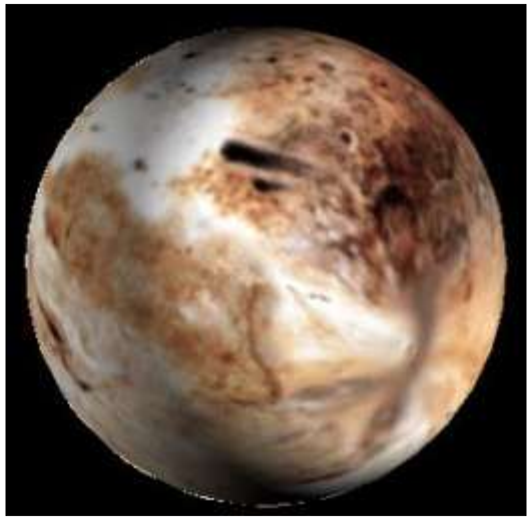


Figure 21. *An image of Pluto produced from Hubble Space Telescope images. Pluto has seasonally varying bright regions that might be regions covered with nitrogen and methane frost.* **NASA FMW 240-11.14.**

Tiny Pluto does have its own moon, Charon, with half the diameter of Pluto, making it almost a double asteroid rather than a planet. Spectroscopy indicates that Pluto is covered with clean, bright nitrogen ice with a little methane frost and solid carbon dioxide mixed in. Charon is darker, probably composed of a dirty water ice with no significant contribution of methane. The surface temperature of Pluto is 50 K (-369 K). At the distance of Pluto, the Sun appears as a faraway point source, like the others stars in the sky, although much brighter.

Summary

What do the outer planets in the Solar System and their moons and rings teach us? Their composition varies with heliocentric distance indicating the conditions under which they condensed. Uranus and Neptune and their satellites are lower in density and richer in easily vaporizable ices, i.e. methane and ammonia ice, than the Saturnian and Jovian systems. Each of the four gas giant planet/satellite systems behaves as a miniature Solar System with a set of satellites orbiting in their equatorial planes. Three of the four planets show evidence of emitting energy generated by their slow gravitational collapse. All are surrounded by rings of orbiting particles. Pluto has properties that are less like those of either the terrestrial or gas giant planets that would suggest it is an escaped satellite of Neptune.

Key Words & Phrases

1. **Belts –** dark, east-west bands of clouds across the surface of Jupiter
2. **Differential rotation –** the variation in rotational period over the surface of a planet
3. **Shepherd satellites**
4. **Spectroscopy –** the study of the spectrum of light emitted from a object
5. **Zones –** light, east-west bands of clouds across the surface of Jupiter

Review for Understanding

1. Which planets have rings?
2. Why is Uranus smaller than Neptune is, but more massive?
3. Is Pluto a terrestrial planet? Why, or why not?
4. How are the Jovian ring systems thought to have originated?
5. How do the Jovian and Saturnian satellites resemble miniature Solar Systems?

Essay Questions

1. Build a scale model for the Jovian satellite system using a beach ball for Jupiter, and appropriate sized balls (e.g., tennis ball, golf ball, baseball, etc.) and fruits or vegetables for the satellites. Report your results. Then, determine how far these objects would have to be separated in order to maintain this scale.
2. Compare and contrast the distinctive features of each of the Jovian planets.
3. Why do Neptune and Uranus differing appearances?
4. Plot the density of the regular Jovian satellites versus their distance from Jupiter. Explain the result.

Chapter 11 - Comets, Asteroids, and Meteorites: Clues to the Formation of the Solar System

An extraordinary atmospheric phenomenon was noticed in this region. At 7:43 a.m. on June 30, a noise as from a strong wind was heard followed immediately by a fearful crash accompanied by a subterranean shock which caused buildings to tremble. One had the impression that some huge beam or heavy stone had possibly struck the building. This was followed by two further equally forceful blows. The interval between the first and third blows was accompanied by an extraordinary underground roar like the sound of a number of trains passing simultaneously over rails, and then for five or six minutes followed a sound like artillery fire. Between 50 and 60 bangs becoming gradually fainter followed at short and almost regular intervals. A minute or so later six more distant but quite distinct bangs resounded and the ground trembled. The intensity of the first explosion may be judged by the fact that horses and people were known to have fallen and windows broken by the vibration. An eyewitness reports before the first bangs were heard, a heavenly body of fiery appearance cut across the sky from south to north, inclined to the northeast. Neither its size nor shape could be made out owing to its speed and particularly its unexpectedness. However, many people in different villages distinctly saw that when the flying object touched the horizon a huge flame shot up that cut the sky in two.
--Krasnoyarets (Siberia) Newspaper, July 13, 1908,
translation from *http://desires.com/1.6/Travel/Siberia/Docs/Siberia2.html*

It is easier to believe that Yankee professors would lie than that stones would fall from heaven.
-- Thomas Jefferson

Chapter Photo. *A Sun-grazer comet. The SOHO spacecraft took this image of a comet, heading towards its meeting with the Sun and ultimate destruction, in December of 1996. This comet is thought to be one of family of Sun-grazing comets that derive from a comet that passed close to the Sun and subsequently broke up. The solar wind is seen along the right-hand side of this picture, emanating from the Sun's surface.* **NASA.**

Chapter Preview

Comets, asteroids, and meteoroids best represent the fossil evidence of our Solar System. It is thought that the Sun and planets formed from the collapse of a huge cloud of dust and gas, triggered by the detonation of a nearby star. What evidence do we have of such an event? Can we determine how the Solar System formed in any detail? As scientists, we must look to our best evidence. The most unaltered remnants of Solar System formation are the smallest, those that have not undergone erosion by an atmosphere or differentiation that occurs on larger Solar System bodies. Comets, asteroids and meteoroids represent the kind of debris that formed from the initial collapse of a presolar cloud and subsequently combined to form the Sun, planets, and their moons. In studying them we hope to learn about conditions in the Solar System shortly after its formation. In the next chapter we will use this evidence to examine candidate theories of Solar System formation.

Key Physical Concepts to Understand: *debris left over from the formation of the Solar System: comets, meteorites, and asteroids*

I. Introduction

There is a great deal of evidence that the small amounts of debris that we observed in our Solar System is a small remnant of a previous era of intense bombardment that produced frequent impacts on all of the planets, that has tapered off until the present time. Those planets and moons with the most ancient surfaces, the Moon and Mercury for example, testify to this episode of intense cratering. Such bombardment was universal and hammered the Earth as well, later to be disguised by erosion and plate tectonics. The survivors of this original space debris, those pieces of rock and ice that chance would allow to escape being swept up by the planets and their moons still exist today, in the form of asteroids, comets, and meteoroids, depending on their size and composition.

II. The Tunguska Event and other Cosmic Impacts on Earth

On June 30, 1908, a remarkable event occurred at a place in Siberia called Tunguska. The Earth was impacted by a large piece of space debris. The event itself was not remarkable, for the Earth and fellow planets have been impacted countless times by larger objects. It was remarkable in that it happened in modern times and was well-observed and recorded by humankind, as if a dinosaur from some bygone age suddenly appeared and walked down a main thoroughfare in our town or city.

The 1908 Tunguska impact event began as an intensely bright fireball was observed streaking across the daytime sky. A series of deafening explosions were heard as far away as 1000 kilometers away followed by smoke and fire emanating from the direction of the impact. Trees within 30 kilometers of the site were knocked down in a direction pointing radially away from the impact, charred on the side facing the impact, and stripped of their branches (Figure 1).

Figure 1. *Taken 21 years after the Tunguska event, this image shows the result of the meteorite on the forest at the impact site.* **FMW 160-7.16.**

It was first proposed that the Tunguska event was caused by the collision between the Earth and a small comet. If the comet exploded in the atmosphere it is possible that it wouldn't have produced an impact crater or left recognizable debris. It is now thought that this is not a reasonable explanation because an icy comet would have exploded too high in the atmosphere to produce the damage seen from the Tunguska event. Now most experts believe that the Tunguska event is consistent with the Earth colliding with an 80-meter diameter, rocky meteoroid traveling at hypersonic speed, about 79,000 km/h**.** Some particles consistent in composition with meteoritic dust were found embedded in tree resin at the impact site. Chris Chyba of Princeton and Paul Thomas and Kevin Zahnle of the NASA Ames Research Center in California modeled the impact and found it consistent with the impact of a 70-meter diameter stony meteorite that exploded in the atmosphere, although the exact culprit is still a matter of debate.

In 1969 hundreds of people watched while an intense blue-white light crossed the night sky near Chihuahua, Mexico. The event was punctuated by an explosion that showered the ground with hundreds of rocks, which turned out to be **carbonaceous chondrites,** all fragments of what is now known as the Allende meteorite. Analysis of these fragments found a short-lived isotope of aluminum that indicates that radioactive isotopes were deposited in the neighborhood of the Sun by an exploding star, or supernova, at the time that this meteorite was formed, and by inference, that the Solar System was formed. This is evidence of a supernova in neighborhood at the time of the Sun's birth. In fact, this supernova may have triggered the formation of our Solar System.

Barringer Crater (Figure 2) near Winslow Arizona was formed from a meteoroid impact about 25,000 years ago. The bowl-shaped crater is 170 m deep, 1260 m in diameter, and has an elevated rim 50 m above the surrounding desert. Nickel-iron fragments discovered in the area along with the crater dimensions indicate that Barringer Crater was excavated by the impact of a 60,000 ton, 25 meter diameter nickel-iron meteoroid striking the desert floor at a velocity of about 15 km/s.

Figure 2. *The Barringer meteorite crater in Arizona is 1.2 km in diameter. The meteorite that produced this crater was approximately 100 meters in diameter. On the right is a shuttle image of the Manicouagan impact crater in Canada (NASA). "Manicouagan Reservoir lies within the remnant of an ancient eroded impact crater (astrobleme). The crater was formed following the impact of a 5 kilometres (3.1 mi) diameter asteroid which excavated a crater originally about 100 km (62 mi) wide although erosion and deposition of sediments have since reduced the visible diameter to*

about 72 km (45 mi).” (*http://en.wikipedia.org/wiki/Manicouagan_Reservoir*). **P 301-18.4.**

These events, among others, show that there is a range of meteorite impacts on the Earth caused by the collision of Earth with space debris in our Solar System having a range of sizes.

In general, material in our Solar System other than the Sun, planets, and their satellites have three classifications: **comets**, **asteroids**, and **meteoroids** (Figure 3). All of these objects orbit the Sun. Comets are solid icy bodies typically a few kilometers in diameter. Asteroids are rock/metallic objects up to 1,000 kilometers in diameter. Meteoroids are smaller debris, probably fragments or asteroids, having circular or elliptical orbits, usually out of the ecliptic plane. If a meteoroid collides with the Earth it can produce either a **meteor** or **meteorite**. A fragile meteoroid that burns up in the atmosphere produces a visibly bright trail or **shooting star**. Some of the denser, larger, more robust meteoroids punch through the Earth’s atmosphere and plummet to the ground. The resulting chunk of space rock/metal on the Earth’s surface is called a **meteorite**. It is theoretically possible for the same object to exist as all three: first as a meteoroid, then a meteor, and finally a meteorite. It is likely that much of these objects are material that is left over from the formation of the Solar System.

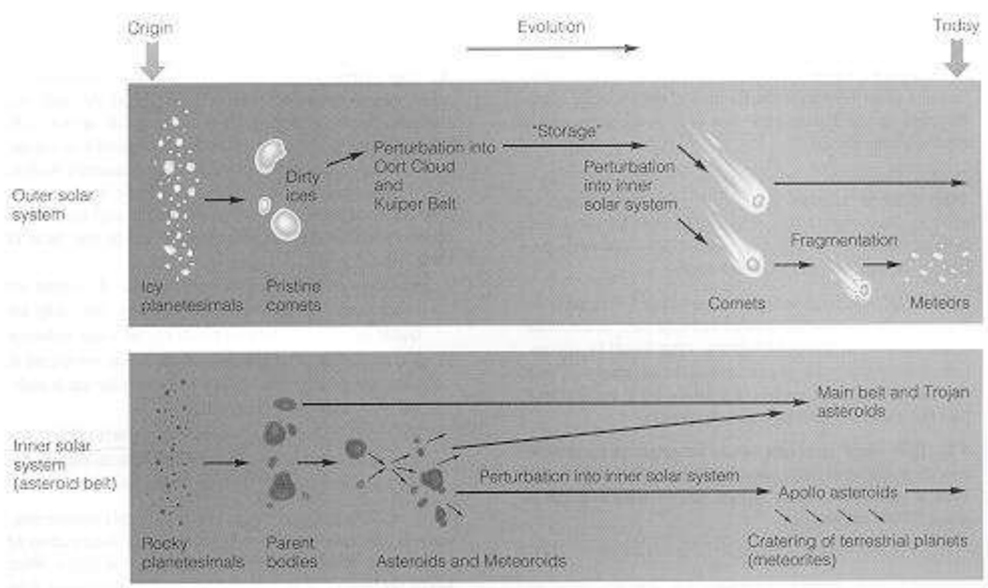
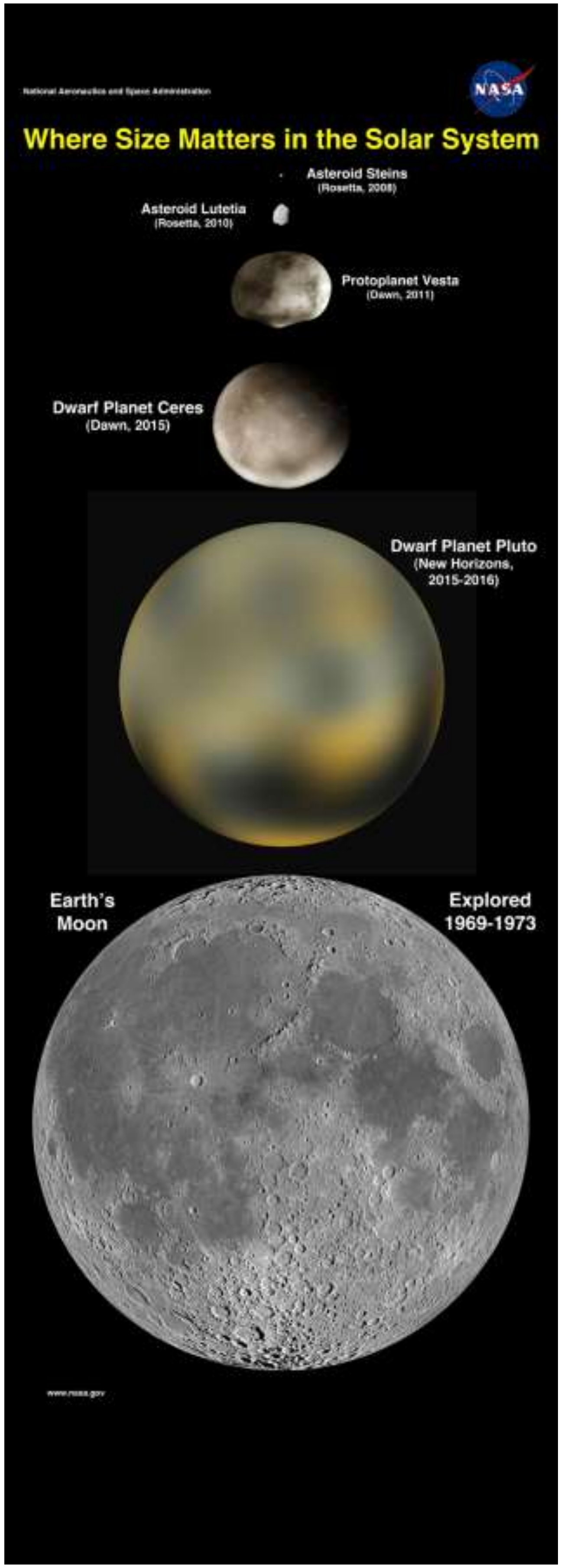


Figure 3. *Diagram of space debris hierarchy.*

WebVideo: The 2013 Meteor
http://www.washingtonpost.com/world/national-security/meteor-impact/2012/09/14/a7661e08-fdea-11e1-a31e-804fccb658f9_video.html?tid=video_carousel_3

III. Asteroids

Asteroids are any large interplanetary bodies that don't emit gas (Figure 4). (Those that do are called comets.) It is entirely subjective at what size limit one stops calling objects asteroids (or comets in the case of icy objects) and starts calling them meteoroids. It is only clear that asteroids are larger than meteoroids. Asteroids are typically made of rocky materials and embedded metals. The spectra (colors) of asteroids are similar to those of meteorites that have been collected on Earth. Analysis of these spectra indicates that asteroids fall into three groups according to composition: basalt-like lavas, rocks containing a high percentage of nickel-iron, and water-rich clays.


Where Size Matters in the Solar System
Asteroid Steins
(Rosetta, 2008)
Asteroid Lutetia
(Rosetta, 2010)
Protoplanet Vesta
(Dawn, 2011)
Dwarf Planet Ceres
(Dawn, 2015)
Dwarf Planet Pluto
(New Horizons,
2015-2016)
Earth's
Moon
Explored
1969-1973

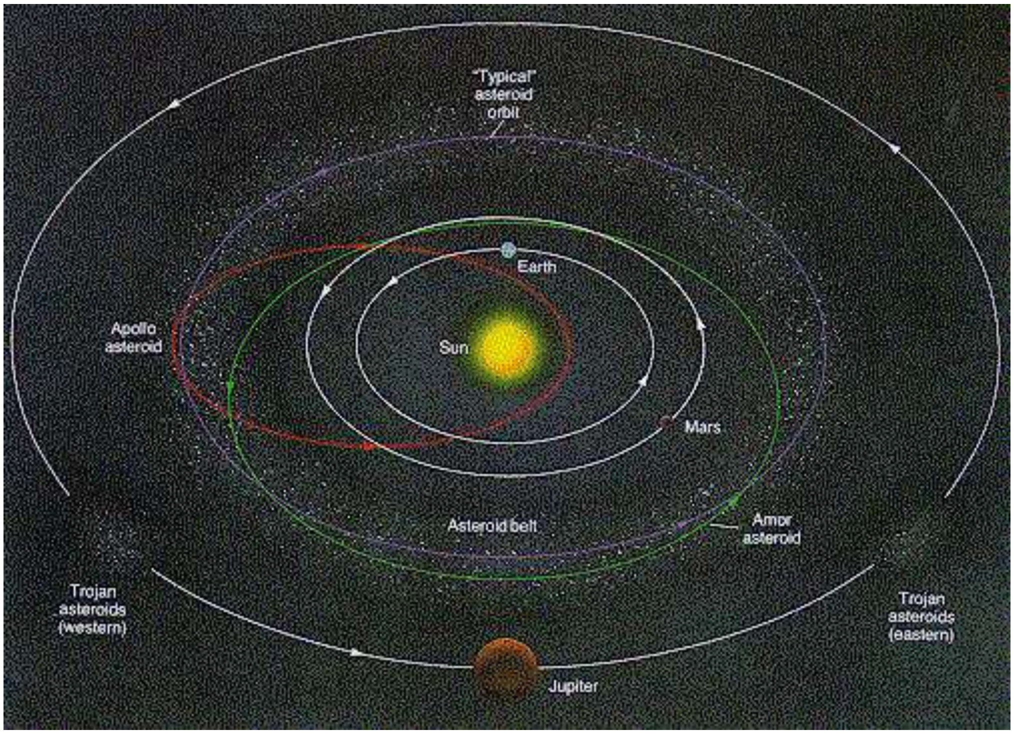


Figure 4. Asteroid orbits and sizes. **Panel A.** Relative sizes of asteroids and moons. **Panel B.** *A sample of asteroid orbits. Asteroid orbits lie in the ecliptic plane. The asteroid belt (shaded) is the home of most asteroid orbits.* **NASA.**

A relationship known as **Bode's Rule** was discovered by the German astronomer Titus and popularized by Johann Bode in 1772. Bode's rule is a numerical recipe for remembering the distances to the planets: First write in a row the sequence of numbers 0, 3, 6, 12, 24… doubling each successive term, one for each planet. Then add 4 to each term and divide the resulting sum by 10. The result is the distance of each of the 9 planets from the Sun. This is not a fundamental law of physics, only a numerical scheme that works, and then with the following exceptions: the planet Neptune is missing entirely and there is no planet at 2.8 AU.

Table 11.1: *Bode's Rule of Planetary Distances from the Sun*

Planet	Mercury	Venus	Earth	Mars	Ceres	Jupiter	Saturn	Uranus	Pluto
1st Series of Nos.	0	3	6	12	24	48	96	192	384
Add 4	4	7	10	16	28	52	100	196	388
÷ by 10	0.4	0.7	1	1.6	2.8	5.2	10	20	39
Actual Distance (in AU)	0.4	0.7	1	1.5	2.8	5.2	9.5	19	39

(Note: The distance to Neptune is not given.)

The discovery of Uranus in 1781 seemed to confirm Bode's Rule. As a result, many astronomers were determined to search for the missing planet at 2.8 AU. On the first day of the 19th century, New Years Day 1801, the Sicilian astronomer Giuseppi Piazzi discovered a faint star-like object moving slowly with respect to nearby stars. He followed this object over several nights and found that its orbit was between the orbits of Mars and Jupiter. Piazzi named it Ceres after the patron goddess of Sicily. Ceres is the largest asteroid, with a diameter of about 940 km and a distance of about 2.8 AU from the Sun.

In 1802 the German astronomer Heinrich Olbers discovered the asteroid Pallas, also between the orbits of Mars and Jupiter. Since then over 6,000 asteroids have been discovered, most in the ecliptic between 2 and 3.5 AU, known as the **asteroid belt**. Most asteroids are smaller than about 100 kilometers in diameter, are irregularly shaped, and are cratered. Only 3 asteroids have diameters greater than 300 kilometers. There are perhaps 100,000 more asteroids that are bright enough to find using earth-based telescopes. At first astronomers believed Ceres to be the long sought after planet at 2.8 AU, predicted by Bode's Rule. But Ceres is only 1000 kilometers in diameter, far too small to be a planet. Even if it is proposed that Ceres is one fragment of a shattered or stillborn planet, all of the subsequently discovered asteroids in the asteroid belt only sum to a mass of about 10% of the Earth's mass. Today it is assumed that Bode's Rule only approximates the phenomenon that forming planets gathered all the material available in their vicinity, prohibiting subsequent planets from forming. The result is simply a healthy spacing between planets. The asteroid belt may simply be a gravitational reservoir formed by Jupiter's gravitation for space debris left over from the formation of the Solar System.

Comparative Planetology III: Why are small Solar System bodies irregularly shaped?

The largest bodies in the Solar System, planets and the larger moons, are all nearly spherical. Moons and asteroids larger than 500 kilometers in diameter tend to be spherical. Moons and satellites smaller than 500 kilometers in diameter are typically irregularly shaped. The reason is the stronger pull of gravity among high-mass objects. Gravity tends to pull massive objects together into the smallest, most compact volume. The more massive an object is the larger is the force of gravity at its surface. For very large, planet-sized objects, such as the Earth, any deviation from sphericity is corrected when the relentless force of gravity acting over millions or billions of years causes flexible objects, such as the Earth's mantle, to flow and compress material into an object where matter is contained within the smallest radius. The result is a sphere. In small objects, gravity is more insignificant and they tend to maintain their original, often highly irregular shape. Many of these moons and asteroids are irregular fragments of larger objects that were shattered by impact.

There are probably a million or more asteroids in the asteroid belt with diameters larger than 1 km in diameter. Contrary to science fiction movies, their average spacing is millions of kilometers. A spacecraft traveling through the asteroid belt is unlikely to suffer a collision.

There are a number of asteroids outside the main asteroid belt. Some cross inside the orbit of Mars; others, the **Apollo asteroids** cross the Earth’s orbit and some will eventually collide with it. These are probably the source of meteorites that are found on Earth. Several asteroids have passed near the Earth in recent history. In 1994, the 10-meter diameter asteroid 1994 XM1 passed within 105,000 kilometers of the Earth (less than 9 Earth diameters). Most Apollo asteroids will eventually strike a planet or moon. Chances of a major collision between the Earth and an asteroid in our lifetimes, or even in the next 1,000 years, is insignificant. Any Apollo asteroid or comet in an Earth-crossing orbit will be swept up by the Earth or other planet in about 10 million years. Because asteroids and comets are continually being thrown our way from the asteroid belt and the cloud of comets in our outer Solar System, this will occur steadily.

In 1983, the Infrared Astronomical Satellite, IRAS, discovered elliptical trails of dust around the Sun, littering the asteroid belt, each probably recording a relatively recent, dust-raising collision between two asteroids.

In 1990 the Galileo spacecraft imaged the asteroids Gaspra and Ida on its way to Jupiter. Gaspra is older with a larger crater density than Ida (Figure 5a). Ida has its own moon, Dactyl, 1.5 km in diameter. Pallas is known to be orbited by its own small satellite. There are several other asteroids with known companions. In 2012 NASA’s Dawn spacecraft imaged the asteroid Vesta (5b).

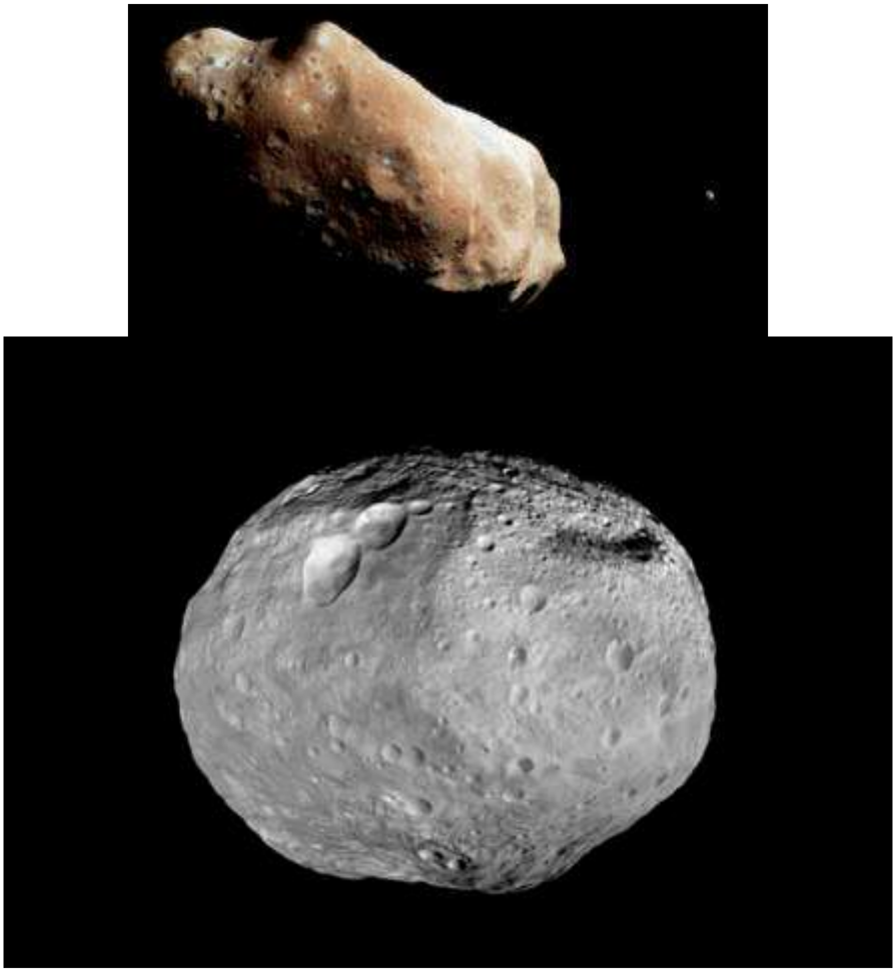


Figure 5. Panel A. *The asteroid Ida (56 km in diameter) and its tiny, orbiting companion Dactyl (1.5 km in diameter). Dactyl is seen on the right-hand edge of this image.* **FMW 253-12.6&12.7. Panel B.** *The cratered asteroid Vesta (525 km in diameter).* ***NASA.*** *From*
http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=14723

WebVideo: Rotation of Vesta
http://en.wikipedia.org/wiki/File:Vesta_Rotation.gif

IV. Meteorites

Meteorites are space rocks that have been discovered on the surface of the Earth. Space debris typically strikes the Earth at velocities between 11 and 60 kilometers/second (24,000 to 134,000 mph). At these velocities, dust and gravel-sized debris burns up from air friction, and can sometimes be seen as meteors of shooting stars. Larger, rock-sized debris is slowed by atmospheric drag but survives impact with the Earth. Although only one or two meteorites are found each year, over 30,000 meteorites grace the displays of museums throughout the world. Approximately 300 tons of meteorites fall to Earth each day. However, large meteorites are very infrequent. In 1972 a 1,000-ton object was observed by a US Air Force reconnaissance satellite to skip off the upper atmosphere over northwestern Wyoming. Such a large meteorite probably impacts the Earth at most a few times a century. A 10,000-ton Tunguska-class meteorite probably collides with Earth every few centuries. A meteorite of the size necessary to produce the Arizona meteor crater is estimated to occur every 20,000 years. The largest impact crater on the Earth's surface is the Vredefort crater, 300 km in diameter, in South Africa. The meteorite that created that crater may have been 5-10 km in diameter.

WebNote: People Struck by Meteorites
http://en.wikipedia.org/wiki/Ann_Hodges

Meteorites fall into three composition classes: **stony meteorites**, **iron meteorites**, and **stony-iron meteorites** (Figure 6). Stones look like ordinary volcanic rocks, although some have distinctive darks crusts, caused by surface melting from air friction as the meteorite passed through the atmosphere.

Figure 6. *A primitive meteorite (carbonaceous chondrite) with individual grains as old as 4.8 billion years, as determined by radioactive dating.*

Iron meteorites have an unusually high iron content that makes them easy to distinguish on the ground. Iron meteorites show nickel-iron crystals up to several centimeters long. These crystals are only found in meteorites because they cooled slowly over millions of years. Because of these distinguishing characteristics, most meteorites that have been identified and put on display in museums are iron meteorites, but stony meteorites represent 95% of the meteorites that strike the ground. Stony-iron meteorites have equal amounts of rock and iron-nickel.

One rare stony meteorite is the carbonaceous chondrite, a primitive type of meteorite that never experienced differentiation. Carbonaceous chondrites contain complex organic compounds and up to 20% water. These organic compounds include **amino acids**, a basic component of proteins, conceivably a terrestrial contaminant. The possibility that meteorites could have introduced one of the basic building blocks of life to the Earth has many ramifications as to the origin of life on Earth. In carbonaceous chondrites water is chemically bound and is expelled only by heating the meteorite to 100s of K. This means that carbonaceous chondrites could not have been part of a larger body that underwent differentiation. It also means that they were formed in the asteroid belt or beyond, where volatiles such as water had the opportunity to condense.

Meteorites exhibit several unique features when compared with terrestrial rocks and aid in their identification. In particular, meteorites commonly exhibit partial melting, welding of individual grains together (like lunar breccia), and a network of fractures. Radioactive dating of meteorites indicates that almost all of them formed over a 20 million-year interval approximately 4.6 billion years ago; so they are much older than the oldest terrestrial rocks.

The compositions of meteorites are too similar to suggest that they were formed individually and separately. Instead, their compositions can be more simply explained if they came from 4 to 30 parent objects, or **parent bodies**, perhaps 100s of kilometers across that were shattered in a collision with other objects. Such a parent body would be similar to the asteroids that we see today. Indeed, visible light spectra of sunlight reflected from asteroids are similar to the laboratory spectra of meteorites, indicating similarities in composition. The three meteorite classes (stony, iron, and clay-like) are similar to the asteroid classes (basalt-like lavas, rocks containing a high percentage of nickel-iron and water-rich clays). In addition, some of the unique features of meteorites can be explained by them having once been incorporated in a larger planetary body that was shattered in a collision.

Some meteorites show evidence of differentiation. The composition of some meteorites is consistent with them having at one time been incorporated in a larger body that underwent differentiation. In particular, bodies such as the Moon that have experienced differentiation have a lower-density silicate crust and a nickel-iron core. If such a body were fragmented by an impact, the remnant debris would have compositions consistent with a differentiated body: ordinary silicate basalts as well as chunks of nickel-iron metal. Stony, stony-iron, and iron meteorites would correspond to parent body fragments from the crust, mantle, and core, respectively. Undifferentiated bodies would show no such evidence of differentiation, but would be primitive chunks of intermediate density and composition. This is exactly what we find in our meteorite collections on Earth: the ordinary basaltic, or stony, meteorites, nickel-iron meteorites, and the primitive carbonaceous chondrites. The later contain a large amount of water, which would be expelled by heating only to few 100s of K. They could not have undergone significant heating or differentiation without having banished their water.

Brecciated meteorites, those showing individual grains of differing composition that have been welded together by impact may have resulted from breccia formed in a layer of regolith, by small impacts, that was later ejected into space by a large, moon-shattering collision.

Meteorites show evidence of a high-energy collision between their parent body and another object. Many meteorites show evidence of being shocked in a high-speed impact, including a network of fractures, melting, and the injection of melted minerals into fracture voids.

V. Comets

Comets are the small icy bodies in our Solar System that swarm around the Sun (Figure 7). Usually these unseen objects are small (roughly one to ten kilometers in diameter) chunks of ice and dust, without noticeable structure. Comets generally have long elliptical orbits around the Sun. These orbits are generally so large that we only see the comet over an infinitesimally small fraction of its orbit. When they approach the Sun, sunlight striking a comet will boil off gas, giving a comet its signature appearance: an enormous tail. In Figure 8 is shown a schematic of comet including its **nucleus**, **coma**, and **tail**.

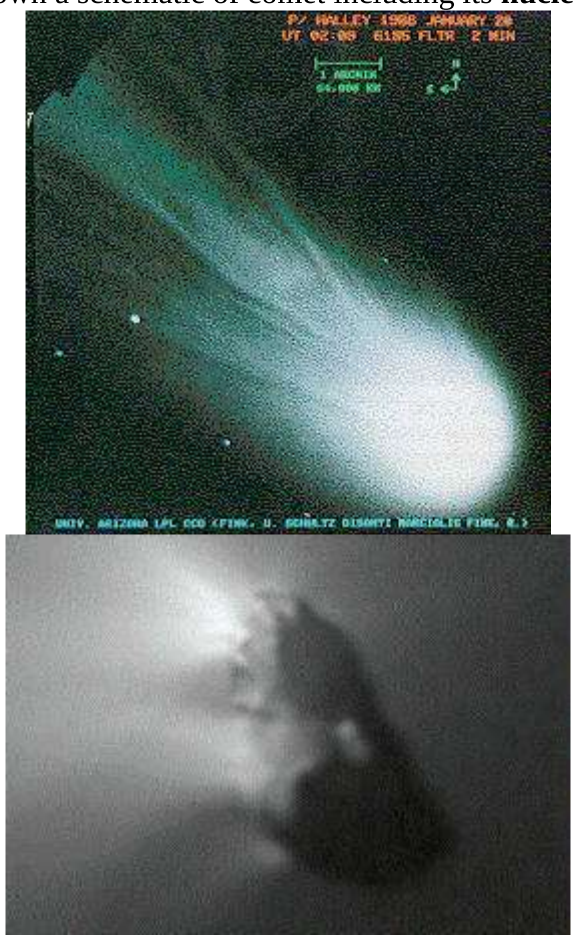


Figure 7. *The head and nucleus of Comet Halley.* **Panel A.** *The head of Comet Halley recorded with an electronic imaging device, called a CCD camera, through a telescope at the University of Arizona in January of 1996.* **FMW 260-12.16A**. **Panel B.** *The nucleus of Comet Halley imaged by the European spacecraft Giotto in 1996. This contrast-enhanced image shows the dark surface of the nucleus, roughly 20 km across, and the bright gases which sunlight has boiled off the dirty-ice nucleus.* **ESA.**

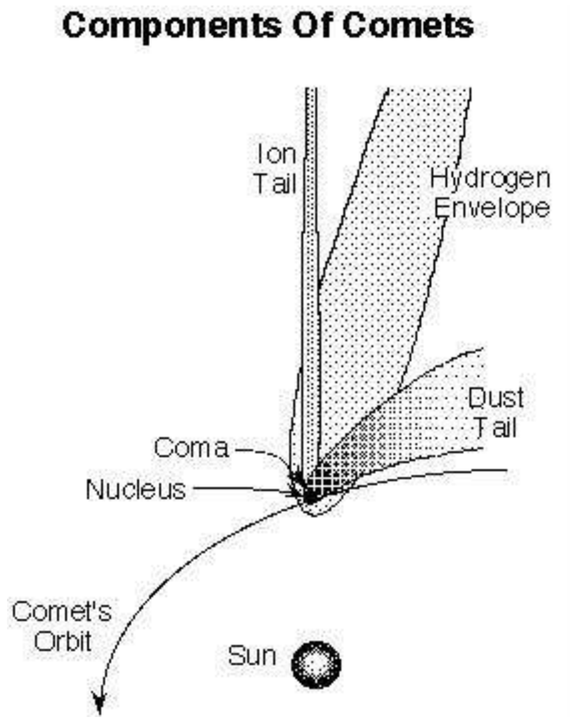


Figure 8. *The structure of a comet. Sunlight and solar wind push the comet gases outward from the Sun, the dust particles in the tail, although pushed by solar wind and sunlight, follow an orbit about the Sun.* **LANL, redraw.**

The comet nucleus is the solid part of the comet and the only part of a comet when it is far from the Sun. As a comet approaches 6 AU from the Sun it begins to form a thick fog of gas and dust enveloping its nucleus. This cloud is called the coma, formed as material is sublimated (transformed from solid to gas) from the comet nucleus. The coma can eventually become as large as the Sun, some 1 million kilometers in diameter. Solar wind particles eventually push the coma gas into a tail of tenuous gas, stretching up to tens of millions of kilometers in length. A separate dust tail is pushed away from the coma in those comets having dusty nuclei. For this reason, comet tails always point away from the Sun no matter what their direction of motion.

Ices and rocky debris are thought to have condensed in roughly equal amounts into small bodies in the early Solar System. Ices include the carbon dioxide, methane, ammonia and water ices that we have seen on solid-surfaced planets and moons. Comets formed in the outer solar system where these ices could condense. Gravitation from the gas giants subsequently randomly scattered them into space in all directions.

There are two families of comets, residing in the **Kuiper belt** and **Oort cloud** (Figure 9). The Kuiper belt of comets lies in a disk beyond Pluto to 500 AU. Nearly 50 comets are observed here; but there may be a reservoir of a billion comet nuclei in the Kuiper belt. Short-period comets, having periods from a few decades to a few centuries to orbit the Sun, are found in the Kuiper belt.

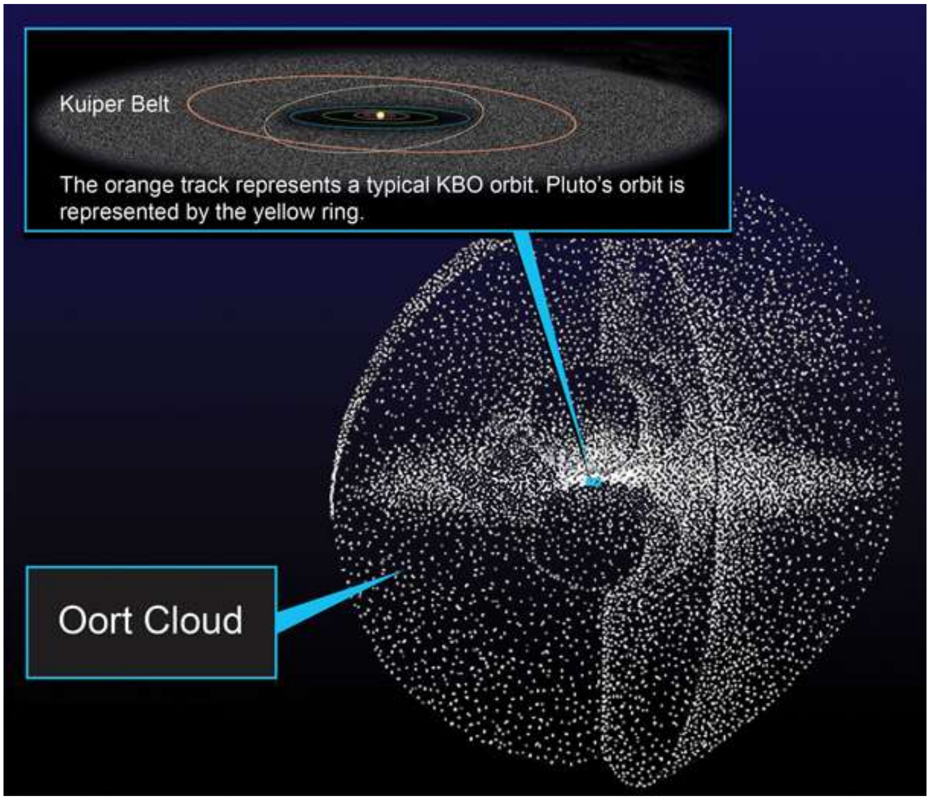


Figure 9. *Schematic of Kuiper and Oort clouds. NASA. From http://solarsystem.nasa.gov/multimedia/display.cfm?Category=Planets&IM_ID=10195*

In the 1950s the Dutch astronomer Jans Oort proposed that several billion comets exist far from Sun, in what is now known as the Oort cloud, a spherical swarm of comets extending out to the limits of the gravitational reach of the Sun, 50,000 AU or one-third the distance to the nearest star. Most Oort-cloud comets have orbits that never get close enough to the Sun to be detected. A passing star can exert enough gravitational influence to perturb one of the Oort comets into an orbit that takes it close to the Sun. The notion that comets are gravitationally bound to the Sun is a likely one since no comet has been observed to leave the Sun with a velocity exceeding its escape velocity.

These long (orbital) period comets thrown into the inner Solar System from the Oort cloud are seen to pass the Sun once and can have orbital periods from one to 30 million years. Long-period comets can be perturbed into short-period orbits having periods less than 200 years, like Comet Halley (which orbits the Sun every 75 years at a maximum distance of 18 AU). A comet can't survive large number of close passages to the Sun, because it typically loses about 1% of its mass at each solar encounter.

A comet can be destroyed when it is disrupted tidally by a planet or collides with it. A prime example was Comet Shoemaker Levy 9 (Figure 10). Shoemaker Levy 9 was fragmented tidally by Jupiter in a 1992 encounter. In 1994, comet pieces returned in their orbits and collided with Jupiter. Such tidal forces are extremely weak and suggest that comet nuclei are fragile and only tenuously held together.

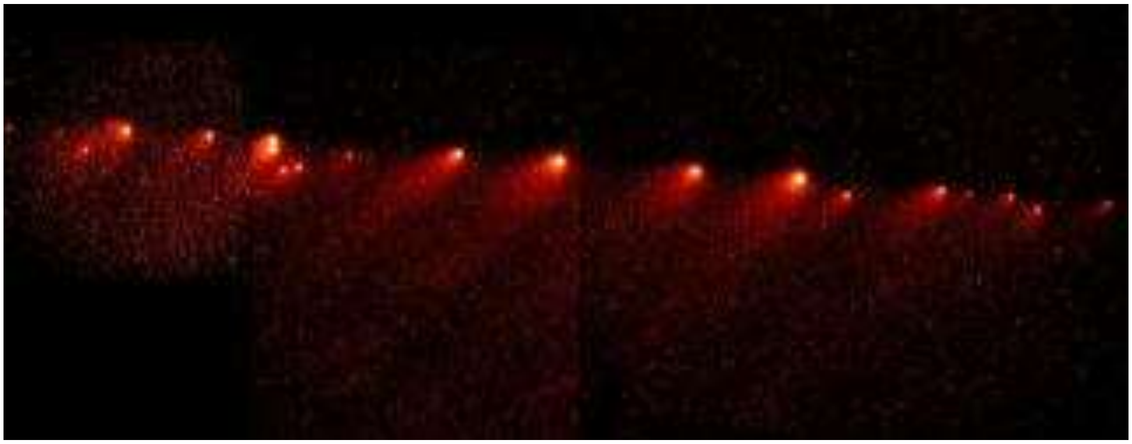


Figure 10. *The pieces of Comet Shoemaker Levy 9 prior to its collision with Jupiter in 1994. These pieces were formed when the comet was tidally pulled apart by Jupiter's gravity when the original comet passed closely by Jupiter in 1992.* **STSI and NASA. FMW 263-12.20.**

Some comets have a single gaseous tail, pushed in a straight line away from the Sun by the solar wind. These are called **Type I comets**. **Type II comets** have a straight gaseous tail and a curved tail of dust (Figures 11 & 12). The dust tail is arched because the dust is pulled into a curved orbit by the Sun's gravity, the dust particles being too massive to be blown into a straight line by the solar wind**.**

Figure 11. *Comet Hale Bopp, the 3rd most luminous comet on record. The gas tail, which appears blue, is pushed directly back from the direction of the Sun by the solar wind. The yellow dust tail is influenced less by the solar wind and more closely follows the comets orbit. This image was made with a four-minute exposure using a conventional camera with a 135-mm wide-angle lens.* **Brian Rachford.**

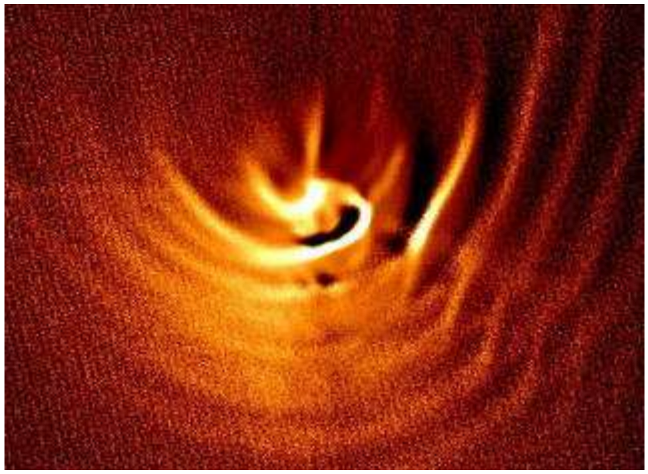


Figure 12. *A telescopic image of Comet Hale Bopp, taken in 1997, showing jets of gas and dust produced by the spinning nucleus. Sunlight striking the dirty-ice surface of the comet vaporizes its ices, which produce jets of gas and dust. The nucleus is spinning with a period of about 12 hours. This spin causes the gas/dust jets to produce this spiral pattern.* **USNO.**

Spectroscopic analysis of sunlight reflected from comets has generated a number of common ions, compounds stripped of one or more electrons, in comet comae which come from solid carbon dioxide, ammonia, water, and methane. Comet spectra sometimes show the existence of dust particles.

Astronomers currently think of comets as dirty snowballs. The materials that form ices in the outer Solar System, water, ammonia, and methane, are commonly seen in comet spectra. Combined with the dust seen in Type II comets, these ices would produce a dirty snow. The fragility of this combination is evident in the breakup of some comets as they pass the Sun.

An Armada of 5 spacecraft (2 Japanese, 2 Russian, and one European) was sent to Comet Halley in 1986 producing the first images of a comet nucleus ever. The European probe, Giotto (after the Italian artist who produced the first known painting of Comet Halley) got as close as 600 kilometers from the nucleus (Figure 7b).

Comets are rich in many of organic compounds on which life is based. Some scientists suspect that comets seeded organic molecules to the planets in their formative stage, creating the initial conditions on Earth for the later evolution of life.

VI. Meteors

Meteors, or shooting stars, are the manifestation of some meteorites that collide with the Earth's atmosphere and burn up from the intense friction with air when they enter the atmosphere at 10 to 40 kilometers/second (22,000 to 135,000 mph) (Figure 13). If one leaves the bright city lights and looks for meteors on a dark night they can typically see 3 to 15 meteors in a one-hour period. There are times when the rate of observed meteors is significantly larger. These meteor showers can have from sixty to 2,000 shooting stars, all apparently radiating from the same direction in the sky. Some showers are even more dramatic. The Leonid meteor shower of November 17, 1966 produced more than 2,000 meteors per minute.

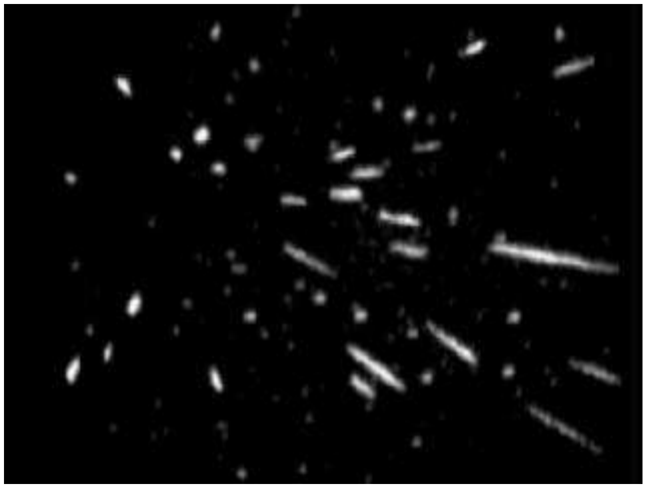


Figure 13. *A time-lapse image of the 1995 Quadrantid meteor shower made from videotape. Each streak is produced by a dust particle glowing as it collides with the Earth's surface at high velocity and burns up. The non-elongated bright spots are background stars. Meteor showers are seen when the Earth crosses the path of an extinct comet and collides with comet material spread along its orbit. Notice that the meteor trails seem to radiate from one point on the sky.* **Molau.**

One prominent meteor shower is the Perseid shower, like other periodic showers, named for the constellation from which they appear to come, Perseus in this case. In 1866 the Italian astronomer Schiaparelli discovered that the Perseids occurred when the Earth crossed the orbit of Comet 1862 III. (Comets are sometimes named for the year of their discovery. In this case, Comet 1862 III was the third comet discovered in 1862.) Comet 1862 III broke up and disappeared after its near-Sun passage. Schiaparelli proposed that major meteor showers occur whenever the Earth crosses a deceased comet's orbit and sweeps up a significant amount of debris that has been spread out along its orbit. Cometary ices are more fragile than the rocky/metallic meteorites that impact the Earth, and are more likely to vaporize on impact with the atmosphere, producing a visible shooting star.

In 1986, the Infrared Astronomical Satellite, IRAS, discovered dust spread out along the orbital paths of active comets. It is thought that most meteors form this way. The Solar System is littered with these trails, and meteors are produced whenever the Earth crosses such a path in its annual trek around the Sun.

Table 11.1: *Prominent Meteor Showers*

Shower Name	Date of max. #	# / hour	Constellation
Lyrids	April 22, am	10-15	Lyra
Perseids	August 12, am	50-100	Perseus
Orionids	October 21, am	20-30	Orion
Taurids	November 7, midnight	10-15	Taurus
Leonids	November 16, am	10-15	Leo Major
Geminids	December 12, am	50	Gemini
Ursids	December 22	15	Ursa Minor

VII. The Dinosaur Extinction

In the 1970s Walter Alvarez and his father Luis Alvarez, of the University of California at Berkeley were studying a 65 million-year-old layer of exposed marine limestone in Italy. This layer is unusual because it has an unusually high abundance of the element iridium in a layer between two limestone layers. Iridium is common in meteorites but extremely rare in the Earth's crust because most of it sunk to the Earth's core. Since then, such an iridium-rich layer has been seen worldwide. In every case it is in clay dated at 65 million years. Coincidentally, it was 65 million years ago that dinosaurs became extinct along with two-thirds of all species.

Walter and Luis Alvarez proposed that some 65 million years ago an asteroid, approximately 10 kilometers in diameter, struck the Earth. Such a collision would have been catastrophic for life on Earth, blasting enough dust high into the atmosphere to block sunlight from the Earth's surface for several years, and dropping the Earth's temperature dramatically. Plants died first, then plant-eating dinosaurs and other vegetarians, and finally meat-eating predators. When dust enriched in iridium from the impacting asteroid finally settled to Earth, it formed an iridium-rich layer of rock-forming sediment.

Later, in 1992, geologists identified the 180-kilometer diameter Chicxulub crater embedded in the Yucatan peninsula as the crater formed from this impact (Figure 14). Glassy debris and shocked grains of rock found in the crater suggest a high-energy impact origin. Radioactive dating of these rocks indicates that this crater was formed 64.98 million years ago.

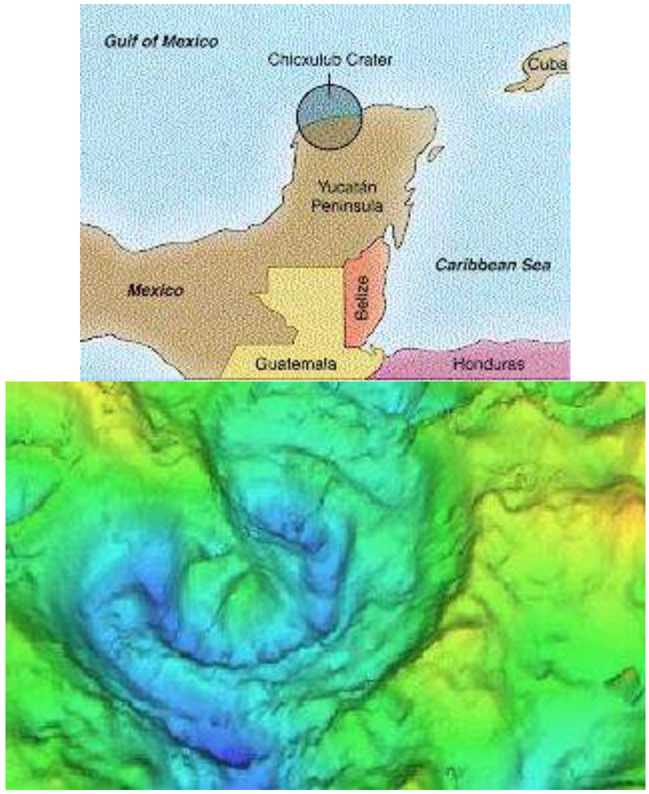


Figure 14. *The Chicxulub meteorite crater on the Yucatan Peninsula.* **Panel A.** *A map showing the location of the Chicxulub crater, the impact that may have caused the extinction of dinosaurs, 65 million years ago.* **FMW 162-7.19. Panel B.** This 3-D model of the Chicxulub crater, from gravity and magnetic field data, shows the outline of an impact crater consistent with a meteorite roughly 20 km in diameter. **Sharpton, LPI.**

Not all geologists believe that the extinction of the dinosaurs was caused by the collision between the Earth and a modest-sized asteroid, but most agree. Large objects strike Earth with megatons of destructive capability, but very infrequently (Figure 15). The time between species-threatening collisions of this kind is about 100 million years.

WebVideo: the Tunguska Impact
http://www.dailymotion.com/video/xtwvk_tunguska-explosion-30-july-1908_news#.UOMkDm9X2So

Webnote: a Catastrophic Impact and the Extinction of Dinosaurs
http://en.wikipedia.org/wiki/Chicxulub_crater

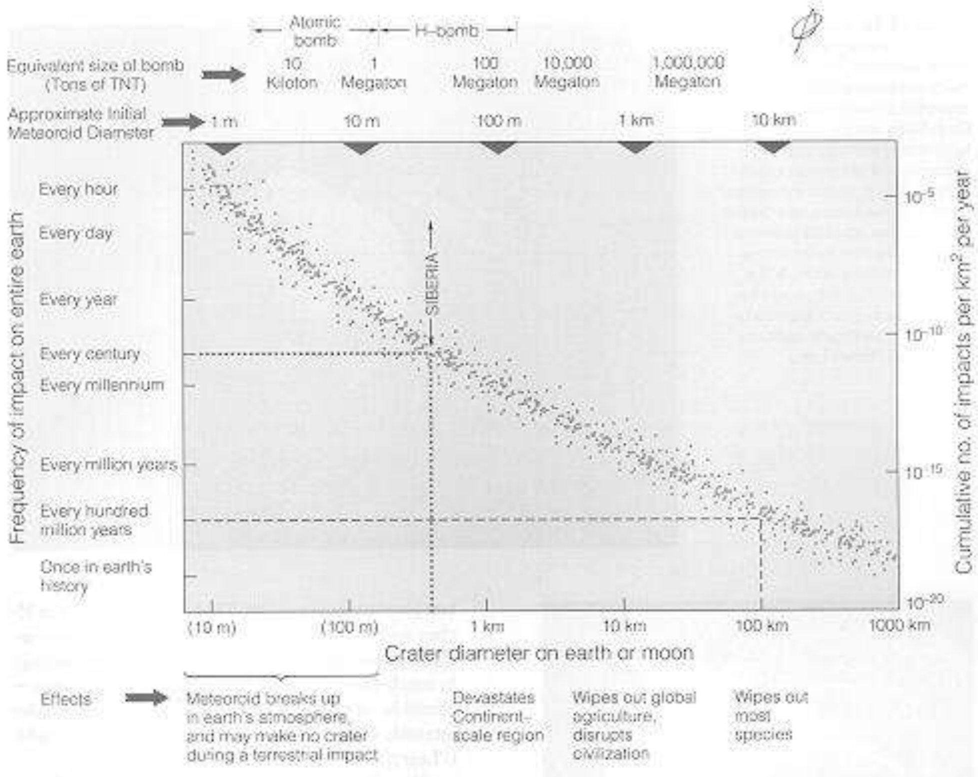


Figure 15. *Frequency of cratering events on the Earth and Moon.*

Summary

Meteorites, asteroids, and comets represent fossil material left over from the origin of the Solar System. These can be studied as clues to the conditions under which our Solar System formed and under which the planets were bombarded by planetesimals, scarring them with impact craters. Meteorites represent 4-30 shattered asteroids, called parent bodies. Meteorites and asteroids are divided into three similar and basic types. The meteorite groups are primitive carbonaceous chondrites, nickel-irons, and basalts. Asteroids are generally found in the ecliptic plane between the orbits of Mars and Jupiter. Comets are icy remnants of the Solar System formation and are found in the further reaches of the Solar System, in the Kuiper belt and the Oort cloud. Meteors represent comet material shed by extinct comets that collides with the Earth in its orbit about the Sun. There is evidence that the extinction of the dinosaurs was a result of a meteoroid impacting the surface of the Earth.

Key Words & Phrases

1. **Amino acid** – an organic compound out of which proteins are formed. A basic building block of life.
2. **Apollo asteroids** – asteroids that cross the orbit of the Earth

3. **Asteroid** - moon-like bodies from 1000 kilometers in diameter down to 100 meter-sized objects orbiting the Sun
4. **Asteroid belt** – a zone in which most asteroids are found, in the ecliptic between 2 and 3.5 AU,
5. **Bode's Rule -** a numerical algorithm for describing the heliocentric distances to the planets
6. **Carbonaceous chondrite –** a primitive clay-like meteorite rich in volatiles
7. **Coma -** a thick cloud of gas and dust surrounding the nucleus of a comet
8. **Comet -** small icy bodies in our Solar System that orbit the Sun
9. **Comet nucleus -** the solid part of the comet and the only part of a comet when it is far from the Sun
10. **Comet tail** – a cloud of low density gas and dust trailing a comet. This gas is vaporized by sunlight and extends up to tens of millions of kilometers in length.
11. **Iron meteorite** – meteorites composed of nickel and iron
12. **Kuiper belt** – a belt of comets lying in a disk from the orbit of Pluto to 500 AU
13. **Meteor -** the glowing trail, or "shooting star", produced by space debris as it passes through the Earth's atmosphere and is heated by air friction **–**
14. **Meteorite** – space debris that has fallen through the Earth's atmosphere and is found on the ground
15. **Meteoroid -** smaller debris, probably fragments or asteroids, having circular or elliptical orbits, usually out of the ecliptic plane
16. **Oort cloud -** a spherical swarm of comets extending out the limits of the gravitational reach of the Sun, 50,000 AU or one-third the distance to the nearest star
17. **Parent body** – the ancestors of meteorites. Parent bodies are thought to have been asteroid-like objects perhaps 100s of kilometers across that were shattered in a collision with other planetesimals.
18. **Shooting star – a glowing trail from** space debris that has fallen through the Earth's atmosphere and is heated by air friction
19. **Stony meteorite** – meteorites made of ordinary volcanic rock
20. **Stony-iron meteorite** – meteorites composed of both volcanic rock and nickel-iron
21. **Type I comet -** comets that have a single gaseous tail, pushed in a straight line away from the Sun by the solar wind
22. **Type II comet –** comets that have a straight gaseous tail and a curved tail of dust

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Review for Understanding

1. Describe the components of a comet.
2. What is the difference between meteors, meteorites, and meteoroids?
3. Summarize the evidence for the existence of bits of material left over from the formation of the solar system?
4. Why is it thought that a meteorite impact caused the extinction of the dinosaurs?
5. What is the relationship between meteors and comets?
6. Discuss the differences in origin between a. carbonaceous chondrites and b. stony and stony-iron meteorites.

Essay Questions

1. What is the difference between a planetesimal, an asteroid, and a parent body?
2. Is Bode's Rule a scientific law? Explain.
3. Why are comets, asteroids, and meteorites thought to be some of the original building blocks of the Solar System, and not simply objects that formed later?

Chapter 12 - Origin of the Solar System

Show me what is left on your plate, and I can tell you who you are.
--French Proverb

Chapter Preview

In this book we examine the five great questions of origin: How did the solar system form? How are stars born? How are galaxies made? How did the Universe originate? How did life on Earth begin? Gravity, the only force dominant over cosmic distances, largely dictates the answer to the first four. Indeed, as we look at objects over size scales from the diameters of planets to galaxies, we see a common morphology: a disk surrounding a massive central object (Figure 1). The common thread is the interaction between gravity and centrifugal force, the first relentlessly compressing matter, the second doggedly resisting, resulting in the ringed planets, orbits the planets in our solar system in a single plane, and the lens-shaped spiral galaxies.

In this chapter we explore theories of the origin of the solar system, including the Sun, its entourage of planets and their moons, asteroids, and comets. We examine the evidence that the Sun and planets formed about 4.6 billion years ago, having condensed from an interstellar cloud of gas and dust, one of many dotting the spiral arms of the Milky Way Galaxy.

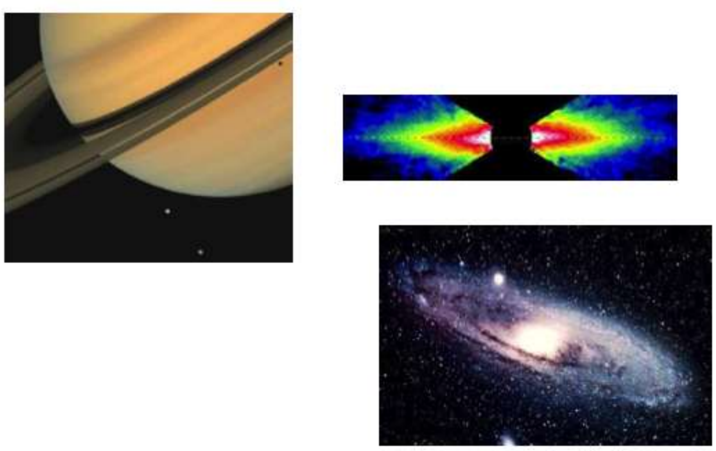


Figure 1. Cosmic Disks formed by the Interaction of Gravity and Centrifugal Force: **Panel A.** Saturn **NASA. Panel B.** An infrared (thermal) image of the dust surrounding the star b Pictoris with a warm preplanetary dust disc seen edge-on **NASA. Panel C.** The nearby spiral Andromeda galaxy (M31) viewed nearly edge-on. **The Electronic Universe Project.**

Key Physical Concepts to Understand: Condensation *of Planets in a Gas Cloud Enveloping the Sun*

I. Introduction

One fundamental theme of both modern and ancient astronomy has been: "How was the Solar System formed?" To ancients, the Solar System (along with a celestial sphere containing the stars) *was* the Universe. In the last half of the twentieth century, scientists have finally been able to develop solid evidence bearing on the formation of the Solar System. Such evidence includes returned lunar samples, laboratory analyses of meteorites, computer models of solar system formation, and telescopic observations of star formation regions. This has led to a widely, but not universally, accepted broad hypothesis that the solar system formed out of a collapsing interstellar cloud of gas and dust, triggered by a nearby **supernova**, an exploding star (Figure 2). We call this the modern nebular theory for the formation of the Solar System. It is the details that are a matter for debate. In later chapters we will examine the formation of stars in general as well as the evidence for planetary systems surrounding other stars. Here we will look at the evidence for formation of our own solar system, much as the sleuth in a whodunit gathers clues to support or refute hypotheses regarding each suspect in a murder investigation. Much of the details of the evidence were explained in previous Chapters (6 - 12); here we look at it as a whole for the first time. Keep in mind that evidence is still being gathered and weighed; the jury is still out.

Figure 2. *Supernova. The Crab Nebula, the remnant of a star that exploded in 1054 AD, expelled its outer layers into interstellar space. It is currently about 10 light years across.*

II. Overview: the Evidence

There are three categories of evidence that directly bear on the formation of the solar system. The first is the strikingly systematic organization of the orbits and rotation of the

Sun, planets and their satellites. This information is not new, and has influenced the development of solar system origin (or **cosmogony**) theories for two hundred years. The other two areas which any theory of cosmogony must explain are the systematic nature of planetary composition, and the measured ages of terrestrial, lunar, and meteorite samples. This information has only been available in the last few decades as a result of space missions and advances in laboratory techniques.

A. Orbits & Rotation.

In order for any theory of cosmogony to satisfactorily explain the observed evidence it must address questions dealing with the gross properties of planetary motion:

- Why do the orbits of the planets (except Pluto) lie in the same plane (Figure 3)?
- Why do the nine planets and asteroids all orbit the Sun with **prograde** revolution (counterclockwise when viewed from the north solar pole)?
- Why does the Sun rotate in this prograde sense?
- Why are the orbits of the planets nearly circular?
- Why do seven of the nine planets have prograde rotation? (With the exception of Venus, which is tidally locked to the Sun, and Uranus, which has its pole lying nearly in the plane of the **ecliptic**.)
- Why does the rotational equator of the Sun and most planets (except for Uranus) lie close to the ecliptic plane?
- Why does **Bode's Rule** describe the nearly regular spacing of planetary orbits? (Each planet has approximately twice the distance to the Sun as its nearest inner neighbor.)

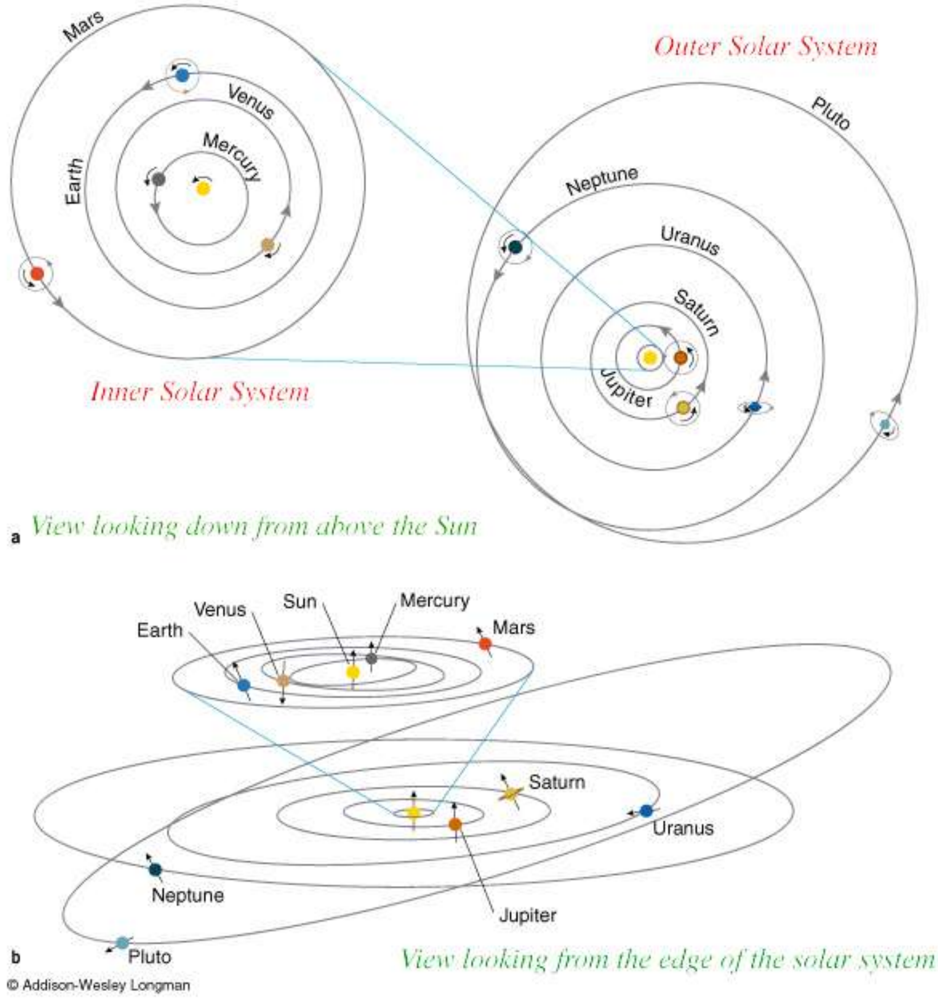


Figure 3. *Inclinations of planetary orbits.*

B. Composition & Age

Just as crucial as planetary motions are to understanding the origin of the solar system are questions of planetary composition: Why do the planets vary systematically in composition and density, with the innermost planets tending toward high density and heavy elements, and the outermost planets tending toward low density and substances of low melting point (Table 1)? Also, the innermost planets are substantially less massive than the outermost planets (except for Pluto). The observed densities of the gas giants (Jupiter, Saturn, Uranus, and Neptune) are consistent with a composition closer to that of the Sun than the innermost planets.

Table 1: Gross Properties of the Planets

Planet	**Mean Distance from Sun** (A.U.)	**Diameter** (Thousands of km)	**Mass** (Earth = 1)	**Mean Density**, (Water =1)	**Inclination of Orbit to Ecliptic**
Mercury	0.39	4.9	0.055	5.4	7.0°
Venus	0.72	12.1	0.82	5.25	3.6°
Earth	1.00	12.7	1.00	5.52	--
Mars	1.52	6.8	0.11	3.93	1.9°
Jupiter	5.20	143	318	1.33	1.3°
Saturn	9.54	120	95	0.71	2.5°
Uranus	19.2	51	15	1.27	0.8°
Neptune	30.1	50	17	1.70	1.8°
Pluto	39.4	2.4	0.03	1.99	17.2°

Meteorites have been dated by measuring the relative abundances of radioactively decaying isotopes and their decay products. Most meteorites have been dated at 4.6 billion years within a period of about 100 million years. The oldest rock samples returned from the Moon have also have been dated at 4.6 billion years, leading most scientists to the conclusion that the Moon, asteroid parent bodies, and the major planets solidified some 4.6 billion years ago over a cosmically short interval: only 100 million years. The oldest rocks on the Earth's surface are only 3.8 million years old, as weathering and plate tectonics have served to remove the primordial surface of the Earth and repave it with more recently formed rock.

III. Theories of Origin

There are two families of theories explaining the origin of our solar system: **catastrophic** and **evolutionary**. The latter is more probable because it does not depend on unlikely special circumstances. Here we follow the theorem called **Ocam's Razor** (named after the fourteenth century philosopher, William of Ocam): when *faced with several competing theories that all explain the observed data to within approximately the same accuracy, the simplest theory should be preferred, as it is the most probable*.

A. Catastrophic

The first catastrophic theory, proposed in 1745 by the Frenchman George Buffon, was based on the collision between the Sun and another star. This collision supposedly produced debris that condensed to form the planets. One of the most modern catastrophic theories was published in 1917 by two Englishmen, Sir James Jeans and Sir Harold Jeffreys. In this theory the Sun suffered a near-collision with another star. Extreme tides ripped matter out of the Sun in a gigantic arc (Figure 4). The matter in this arc subsequently condensed to form planets, like beads on a string. This tidal theory explains most of the gross orbital and composition features of our solar system, and was generally accepted in some form until about 1930.

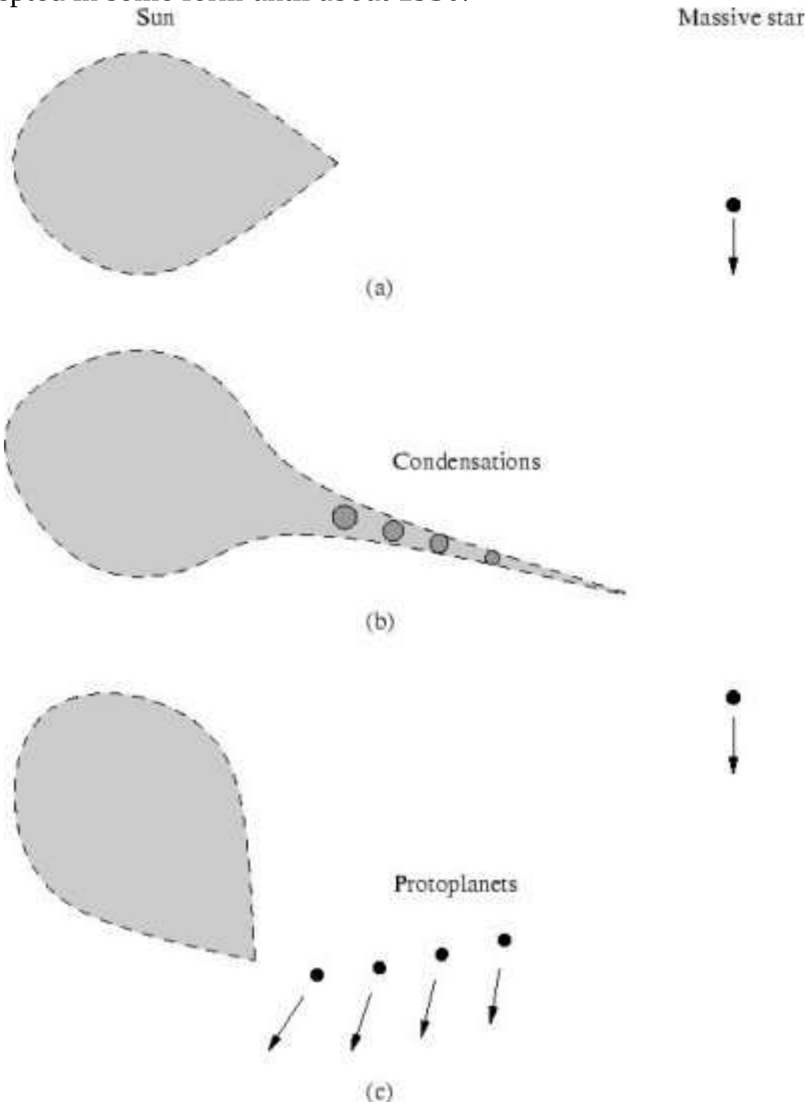


Figure 4. *The catastrophic hypothesis of Jeans and Jeffreys. The Sun suffers a close encounter with another star. Matter is ripped from the atmospheres of both stars in an elongated filament. Out of this stream of gas planets condense as beads on a string, orbiting the Sun in one direction. From* http://www.daviddarling.info/encyclopedia/J/JeansJefftidal.html

B. Evolutionary

Various evolutionary theories have been proposed since 1644, when René Descartes proposed that stars and planets condensed out of eddies in an interstellar gas. Little observational evidence was available to support any evolutionary theory until after 1950. Now, after sample return missions from the moon, modern geochemical studies of meteorites, and advanced computer models of possible solar system scenarios, dramatic progress has been made. It is generally accepted by modern astronomers that the solar system formed in the gravitational collapse of an interstellar cloud of gas and dust into a disk, about 4.6 billion years ago. This agrees with most, but not all, of the observed age, composition, and orbital evidence. A major advantage of this modern nebular theory over the catastrophic theory is that the same scenario invoked to describe the formation of the Sun is also used to explain the formation of the surrounding planets, comets, and asteroids. No special circumstances are needed for forming the planets, giving a simpler, more probable theory.

IV. Catastrophic Theory: Evidence for a Near-Collision with a Passing Star

Both catastrophic and evolutionary theories were developed to explain the orbital and spin characteristics of the planets and their satellites. Both involve preplanetary gaseous matter in prograde orbits around the Sun, in the plane of the ecliptic. Both hypothesize that the planets condensed out of this gas, resulting in planets with prograde spin and revolution, with orbits lying in the plane of the ecliptic.

The catastrophic theory was eventually found to have many flaws including:

- it did not satisfactorily explain the spin, or **angular momentum**, measured in the planets,
- it is improbable that the gas from the Sun would have cooled sufficiently to condense planets before it dispersed,
- it did not account for formation of planetary satellite systems, and
- close encounters between stars in our galaxy are extremely rare.

The latter point is a flaw of all catastrophic theories of cosmogony, making them unlikely.

V. Evolutionary Theory: Evidence for the Gravitational Collapse of an Interstellar Cloud

The most widely, but not universally, accepted theory of cosmogony is based on the collapse of an interstellar cloud of gas and dust into a lens-shaped disk, which eventually coalesced to form the planets. We divide this formation into seven phases (Figure 5):

1. the initial collapse and fragmentation of an interstellar cloud,
2. the free-fall of material in a cloud fragment to form a preplanetary disk,
3. the internal heating of the disk until pressure balances gravity,
4. the condensation of liquid droplets and/or solid grains,
5. the formation of the Sun
6. the coagulation of grains to form planetesimals,
7. the gravitational accumulation of planetesimals to form planets and the early evolution of the protoplanets into the planets as we know them.

WebVideo - Formation of the Solar System
http://video.pbs.org/video/1790621534/

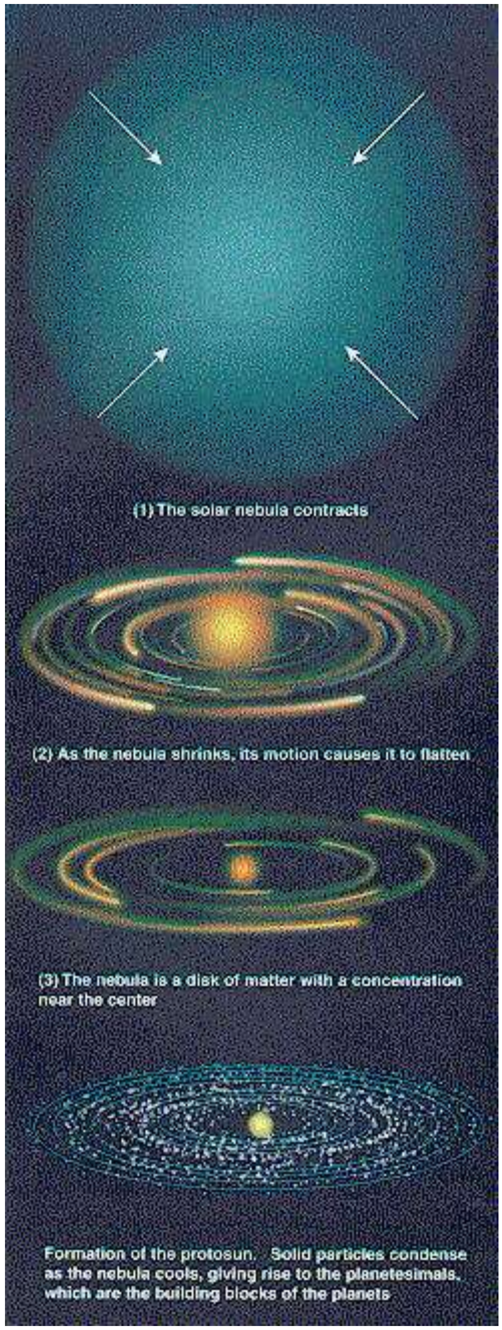


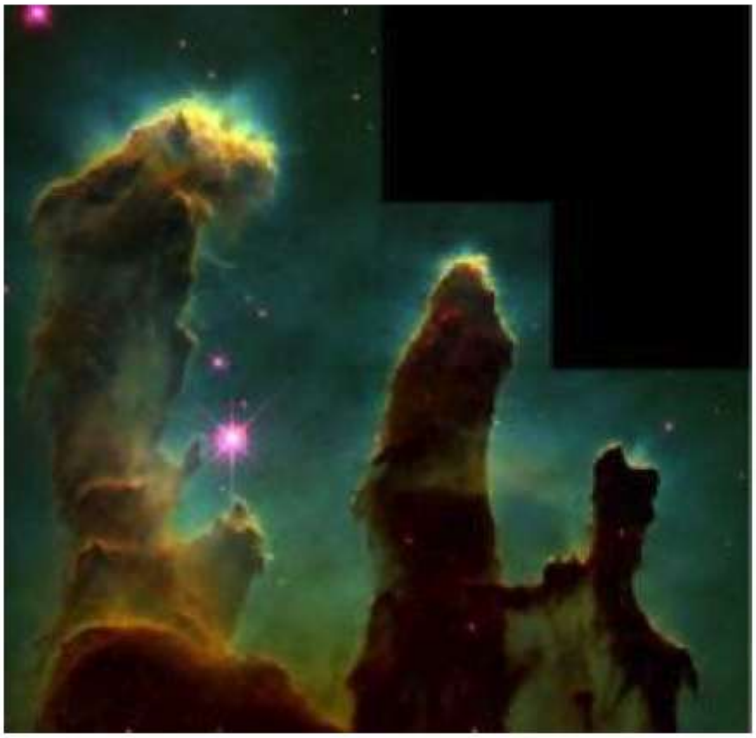
Figure 5. *Birth of the Solar System: 1. the initial collapse and fragmentation of an interstellar cloud, 2. the free-fall of material in a cloud fragment to form a preplanetary disk, 3. the internal heating of the disk until pressure balances gravity, 4. the condensation of liquid droplets and/or solid grains, 5. the formation of the Sun, 6. the coagulation of grains to form planetesimals, and (not shown) 7. the gravitational accumulation of planetesimals to form planets and the early evolution of the protoplanets into the planets as we know them.*

A. Phase 1 - Initial Collapse

The Sun and planets formed from a turbulent presolar **nebula**, or cloud of gas and dust. Gravity caused this gas cloud to collapse; as the collapse occurred, cloud turbulence caused it to split into spinning/rotating fragments. As some fragments collapsed, they spun faster, much as a spinning skater who draws in his/her arms to spin faster.

WebVideo - Conservation of Angular Momentum (Spin)
http://www.youtube.com/watch?v=0k276y9kuQQ

Evidence: Astronomers have found that current and recent star formation is going on in giant clouds of gas and dust (Figure 6). Other evidence, based on meteorite isotope abundances, suggests that the cloud collapse was triggered by the explosion (supernova) of a nearby star, which sent a shock wave into the presolar nebula, compressing cloud fragments and causing them to collapse. This event apparently seeded the presolar nebula with dust grains condensed from the gas expelled from the exploding star. These dust grains were later incorporated into a primitive form of meteorite, the **carbonaceous chondrite**. *Carbonaceous chondrites have small embedded grains with elemental abundances different from the rest of the meteorite, indeed, different from other solar system rocks, but consistent with the composition of dust expected to be produced by a supernova.*



Star formation in a collapsing molecular cloud. HST image of the Eagle Nebula.

Figure 6. *Star Formation in a Collapsing Molecular Cloud. This Hubble Space Telescope image of M16 shows star formation at the ends of columns of gas and dust.*

B. Phase 2 - Free Fall & Formation of a Preplanetary Disk

In the initial stage of contraction, gravity caused gas and dust to free-fall (i.e., without resistance) toward the center of the presolar nebula's mass. The collapse of the gas cloud is slowed at the equator by **centrifugal force** associated with the spinning gas cloud. At the poles of the cloud, matter could fall relatively unimpeded. The result was a lens-shaped cloud about 100,000 A.U. in diameter. In order for spin to be conserved, the spin rate of the collapsing cloud must have increased as the cloud became more compact.

Because of centrifugal force, the solar nebula became a flattened, spinning gas cloud with a central mass condensation that would eventually form the Sun.

Evidence: This phase explains the orbits of the planets in a single plane and their prograde orbits and spin; the initial spin of the preplanetary disk is transferred to the *spin and orbital motions of the planets. Moreover, such preplanetary dust disks have been seen surrounding infant stars (Figure 7).*

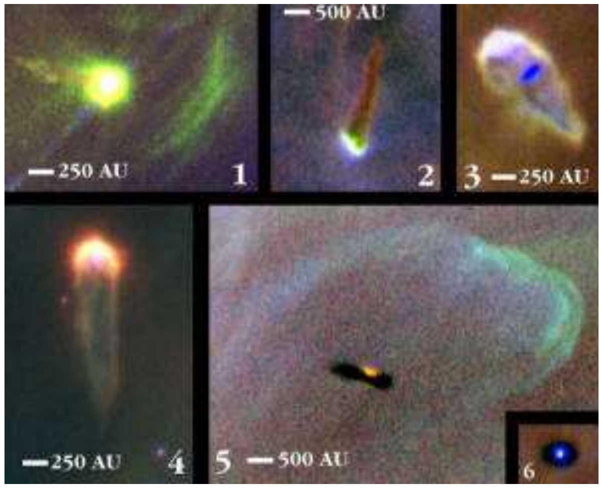


Figure 7. *Young stars in the Orion Nebula are surrounded by preplanetary dust disks. HST images, NASA.*

C. Phase 3 - Pressure Balances Gravity

As the density of the central part of the cloud increased, the gravity became partially balanced by gas pressure, which increased in temperature as the gravitational potential energy was converted to **kinetic energy** (energy of motion) of the gas molecules in the cloud collapse. The temperature of the cloud center might have reached a temperature of 2000° C, great enough to vaporize interstellar dust, while the outer edge of the nebula still remained quite cold (10's of degrees C). Which molecules remained in solid form (dust) and which vaporized depends on the temperature of the gas, which is in turn dependent on the distance of the gas from the center of the nebula (Figure 8).

Evidence: Based on the composition of ancient meteorites (and spectroscopy of other stars and nebulae), the presolar nebula is thought to have had a composition near that of the Sun, 70% hydrogen, 28% helium, 2% carbon, nitrogen, and oxygen, and a trace of other, heavier elements. This supports the theory that the Sun and planets formed from the same presolar nebula.

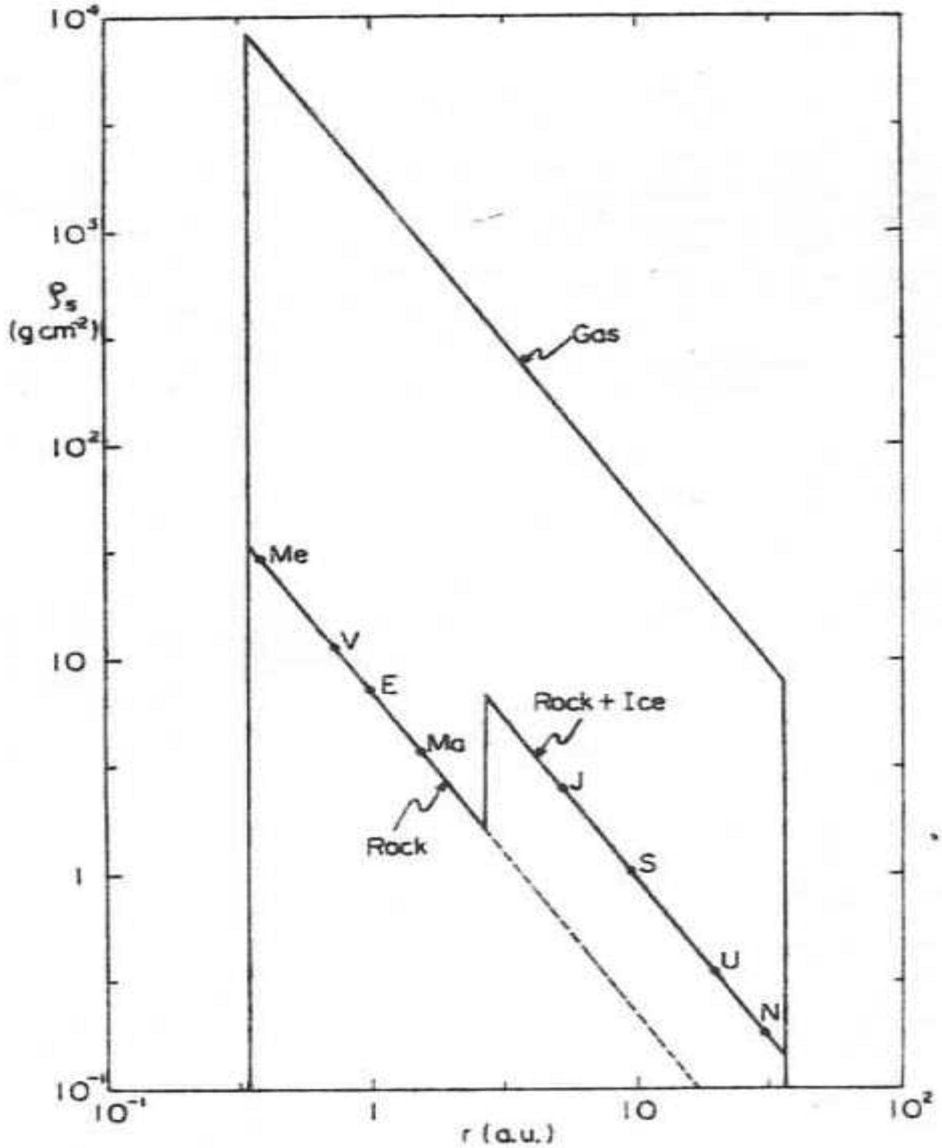


Figure 8. *The Snow Line, composition, and therefore density, of planets varies with its distance from the Sun. There is a sudden jump in planet density between Mars & Jupiter, because ice can freeze – the* ***snow line.*** *Ice increases the amount of solid grains available for coagulation and incorporation into a planet. Rocky planets, which are relatively dense, formed inside the snow line. Gas and ice giants, which are less dense, formed outside the snow line.*

D. Phase 4 - Condensation of New Dust Grains

As the nebula cooled, liquid droplets and solid dust particles formed. This process is similar to water droplets and ice crystals condensing in the atmosphere to form clouds. Because of high temperatures, very few substances could condense inside 0.5 A.U. (the distance of Mercury) (Figure 8). From 0.5 A.U. to the asteroid belt, condensing dust would be of iron or silicate composition. It would be cold enough outside the asteroid belt to condense water, ammonia, and methane ice particles as well. This suggests that planets formed in the outer part of the solar system should have near-presolar nebular abundances, having the potential to condense everything into solid form but hydrogen and helium, the most abundant ingredients of the preplanetary nebula. Although hydrogen and helium could not condense at even the lowest temperatures of the preplanetary nebula, the outer planets became large enough to gravitationally accumulate hydrogen and helium in gaseous form.

Evidence: The density and composition of the planets varies systematically with heliocentric distance. The innermost planets are composed almost entirely of dense, **refractory** *(high melting point) elements and compounds; the outer, gas giants have low densities, consistent with volatile composition (and a rocky core).*

E. Phase 5 - The Sun Turns on

At some point, the central mass of the cloud reached one million degrees C, hot enough to ignite nuclear fusion; the infant Sun "turned on" in a so-called **T-Tauri** phase, in which young stars vigorously eject gas. When the Sun formed it began generating energy as sunlight. This in turn heated the gas cloud from the center, and stabilized the nebula gas pressure. At this point the gas cloud was much hotter in the center than at the periphery. Because of the temperature difference between the inner and outer nebula, volatile molecules could only continue to accumulate in the outer solar system.

Evidence: Newly formed T-Tauri stars, ejecting large amounts of gas, are found in clouds of gas and dust.

F. Phase 6 - Formation of Planetesimals

Solid particles and/or liquid droplets underwent collisions and combined, especially where the cloud temperatures were low and the cloud density was high. Since dust grains are too small to collect gravitationally, they are thought to stick together. This could happen at high temperatures when the grains are partially molten, or at lower temperatures where ice- or organic-coated grains would stick after colliding. The dust grains combined with other dust grains, forming bigger particles: first pebbles, then boulders, and kilometer-sized objects - which we call **planetesimals**, the building blocks of the planets and their moons. Then gravitational attraction between planetesimals began to collect these objects until eventually planets and their satellites are formed. It is believed that asteroids, comets, and meteorites represent some original primeval planetesimals, in modified form.

Orbiting particles settled into a nearly circular traffic pattern around the Sun. Particles with non-circular orbits were held up in traffic by collisions with other particles. Particles orbiting the Sun in circular orbits traveling with neighboring particles at the same speed, like autos on Earth when traveling in their own lanes at the same speed, did not suffer collisions and remained in these preferred paths. Computer simulations show that particles in the preplanetary disk would coalesce into planets having nearly circular orbits.

After growing to 100 km or more in diameter, planetesimals would have started to grow quickly by sweeping up neighboring matter gravitationally. Some planetesimals would grow and combine, eventually forming the terrestrial planets (Mercury, Earth, Mars, and Venus) and the cores of the gas giants. Others would collide and fragment, impact terrestrial planets forming large craters and impact basins, or come close enough to a planet to be gravitationally ejected from the solar system. Most planetesimals could not last longer than about 100 millions years without being swept up by a protoplanet. Planetesimals at nearly the same distance from the Sun would be likely to combine, resulting in a regular spacing between planets, such as described by Bode's Law. Protoplanets collected much of the available hydrogen and helium in their vicinity, growing quite large.

The Sun eventually blew away most of the remaining volatiles in the inner solar system by a strong **solar wind**, gas boiled off its surface at high velocity. It would appear that the presolar nebula had much more mass than the current solar system, much of it having been lost as the Sun turned on.

Evidence:

- *dust clouds of silicate composition are observed around recently formed stars,*
- *the chemical composition of meteorites indicate that they came from fractured planetesimal-sized bodies,*
- *comets and asteroids appear to be planetesimals or fragments of planetesimals,*
- *the extensive cratering on the surfaces of the terrestrial planets, satellites, and asteroids record an episode of steady bombardment of the inner planets by planetesimal-sized bodies*
- *nearly circular orbits of the planets, and*
- *the regular spacing between the planets.*

G. Phase 7 - Early Evolution of the Planets

Planetary formation occurred about 4.6 billion years ago. First protoplanets formed by the accumulation of planetesimals in the solar nebula. As planetesimals collided forming larger masses, and were bombarded by smaller projectiles, these protoplanets were heated past the melting point for solid rock by these high-energy impacts. The resulting protoplanets were probably molten throughout. It may have been such a collision that literally knocked Uranus off its axis, leaving its pole in the ecliptic plane. After most of the larger debris in the solar system was incorporated into the protoplanets, they began to cool, forming solid surfaces. The planetesimals and smaller debris left in the solar system bombarded and cratered planetary surfaces for almost a billion years, leaving the surfaces scarred with craters, many that we still see today on the surfaces of the Moon and Mercury, and to a lesser extent Mars. **Weathering** has removed all but a few crater remnants on the Earth.

Planets with a large enough mass could not only retain a rocky/metallic core but also a thick atmosphere. For the gas giants, they enveloped themselves in a thick shroud of hydrogen and helium, the most abundant ingredients of the solar nebula.

While the planets were still in an entirely molten state they began the process of **differentiation,** with the lower density compounds floating to the outer surface of the planets and the highest density material (nickel-iron) sinking to the core.

Evidence: Based on the ages of terrestrial rock samples, lunar return samples, and meteorites, the age of the solar system is estimated to be 4.6 billion years. An episode of extensive cratering has been recorded in craters on the Moon, other natural satellites, Mercury, Venus, Mars, asteroids, and even the Earth. The effects of weathering via wind and water are seen on the surfaces of the Earth and the other terrestrial planets. Differentiation has caused the Earth to separate into a dense core, a mantle of intermediate density, and a crust floating on the mantle. Differentiation is also supported by the composition of meteorites, which appear to be fragments of shattered planetesimal/parent body. The densities of the gas giants are consistent with a rocky/metallic core surrounded by volatiles in solid, liquid, and gaseous form.

VI. **The Modern Nebular Theory Applied to Satellites, Asteroids, and Comets**

How do the smaller solar system bodies fit with the modern nebular theory of cosmogony? Let's see how this theory explains the characteristics of natural satellites, asteroids, and comets.

A. Satellites

The larger planetary satellites have prograde spin and prograde, circular orbits in the equatorial plane of their primary planet, and are regularly spaced in their distance from their primary planet, mimicking the orbital characteristics of the planets with respect to the Sun. The formation of planetary satellites must be strongly linked to the formation of the planets themselves.

Theories of satellite formation fall into two scenarios:
1. Satellites formed along with their mother planet.
2. Satellites formed elsewhere in the solar system and were later captured by their primary planet.

The first theory is thought to explain the larger satellites, which in general have prograde, circular orbits in the equatorial plane of their mother planet. The second theory would explain those smaller satellites that have irregular orbits: retrograde, highly elliptical, and inclined to the equatorial plane.

The larger, inner satellites of Jupiter and Saturn have **regular** (circular, prograde, and low inclination) orbits and exhibit a regular increase in orbit spacing with distance from the primary planet. It is thought to be likely that these satellites formed from a rotating, flattened disk surrounding the mother planet, much as the solar system formed in a flattened disk around the Sun.

The regular satellites of Jupiter exhibit a decreasing density with increasing distance from Jupiter. This may be a result of the temperature gradient in the gas/dust disk surrounding Jupiter at the time of satellite formation, just as a temperature gradient is used to explain the variation in composition of the major planets. Planetary satellites, with the exception of Saturn's moon Titan, are not large enough to have retained volatiles.

Nearly all of satellites of the gas giant planets can probably be explained by capture of rogue solid bodies in the early solar system. After capture, these satellites could have had a variety of orbital parameters, including prograde or retrograde orbits, high orbital inclination, and highly elliptical orbits.

Only two of the terrestrial planets have satellites: Mars and Earth. Mars has two small satellites with asteroid-like composition, and are thought to have been captured. The Earth's Moon is the largest moon in the solar system compared with the primary planet, except the satellite of Pluto, Charon. The Moon is also the best-studied satellite in the solar system, but there is still no overwhelming consensus among astronomers on how it formed. The four major theories of the origin of the Moon are:

1. The Earth captured the Moon.
2. The Moon was formed along with the Earth as the regular Jovian satellites formed with Jupiter.
3. The Moon's mass was pulled out of the mass that formed the Earth.
4. An asteroid slammed into the Earth, formed a ring of debris close to the Earth, out of which the Moon condensed.

Each of these theories, but the last, has had major problems explaining all of the available data.

B. Asteroids

The asteroid belt, between the orbits of Mars and Jupiter, was originally thought to have consisted of the rocky and metallic remnants of a planet that had failed to form out of the available planetesimals, or had formed and been subsequently shattered. However, the asteroid belt has far too little mass if collected into one body to be called a planet. It is more likely that the proximity of the huge planet Jupiter served to collect much of the available matter near the asteroid belt, starving the region of planetesimals.

C. Comets

Comets, kilometer-sized chunks of ice and dust, inhabit the outer solar system. The vast majority of comets, estimated in the billions, are found in a 100,000 A.U. diameter cloud, the Oort comet cloud, surrounding the Sun. Another smaller group, of which 50 are known, are found in the plane of the ecliptic out to about 500 A.U (the Kuiper belt).

Comets are mostly composed of water, methane, and ammonia ice, which were condensable further out than the asteroid belt in the presolar nebula. There are two main explanations for their formation:

1. Comets formed in the outer solar system and were ejected into the Oort comet cloud by the gravitational influence of the gas giants.
2. Comets formed outside the solar system but were swept into it as it traveled through space.

VII. Conclusion

Much remains a mystery about the formation of the solar system. Current theories are sparse, based on a small amount of existing data, and are not universally accepted by the scientific community. Future space missions, ground-based observing, and laboratory studies will add greatly to our knowledge of solar system formation. Theories will change dramatically in the coming decades.

Summary

The most widely accepted solar system formation hypothesis is that the Sun and planets formed about 4.6 billion years ago, having condensed from an interstellar cloud of gas and dust, triggered by a nearby supernova. Supporting evidence includes samples returned from the lunar surface, laboratory analyses of meteorites, and telescopic observations of star formation regions.

We divide this formation into seven phases: 1. the initial collapse and fragmentation of an interstellar cloud, 2. the free-fall of material in a cloud fragment to form a preplanetary disk, 3. the internal heating of the disk until pressure balances gravity, 4. the condensation of liquid droplets and/or solid grains, 5. the formation of the Sun, 6.the coagulation of grains to form planetesimals, and 7. the gravitational accumulation of planetesimals to form planets and the early evolution of the protoplanets into the planets as we know them.

Key Words & Phrases

1. **Cosmogony** - the study of the origin of the universe.

2. **Nebula** - an interstellar cloud of gas and dust.
3. **Ocam's Razor** - (named after the fourteenth century philosopher, William of Ocam) the principle of preferring the simplest theory when faced with several competing theories.
4. **Planetesimals** - planetary bodies 1-100 km in diameter, which combined to form the early planets.
5. **Regular satellites** – satellites in nearly circular prograde orbits lying in or near the equatorial plane of their mother planet.
6. **Refractory Elements** - elements and compounds, such as iron and nickel, that can condense at high temperatures.
7. **Solar Wind** - the flow of particles from the Sun's outer atmosphere
8. **Supernova** - a stellar explosion in which a high mass star increases its luminosity by one million, expelling a large fraction of its mass into interstellar space.
9. **T-Tauri** - a very young star, exhibiting variations in brightness and episodes of gas ejection.
10. **Volatiles** - elements and compounds, such as hydrogen, water, and ammonia, that only condense at very low temperatures.

Review for Understanding

1. Summarize the modern nebular theory for the origin of the solar system.
2. Summarize the catastrophic tidal theory for the origin of the solar system.
3. What are the main problems with the tidal theory of cosmogony?
4. Why does the Sun contain mostly hydrogen and helium, but the inner planets don't?
5. How does the modern nebular theory explain the differences between the terrestrial and gas giant planets?
6. Discuss the evidence for there having been a large number of planetesimals in the Solar System at one time.
7. Give five observations of the Solar System and explain how they lead us to believe that the Solar System condensed out of a cloud of dust and gas.

Essay Questions

1. What would the solar system look like if the planetesimals had formed before the presolar nebula had collapsed to a disk?
2. What is the difference between an ordinary rock, found at the side of the road, and a meteorite?
3. Describe how our solar system would now appear, if the interstellar gas out of which it formed had been composed entirely of hydrogen and helium.
4. Has the evolutionary theory given up all forms of catastrophism? Explain.
5. What are the weak points of the modern nebular theory of solar system formation? What evidence could be gathered to support or contradict these points?

6. Why is it that planets move in counterclockwise, circular orbits in the ecliptic but comets have randomly inclined, non-circular orbits which are both clockwise and counterclockwise?
7. If the Earth formed in the same gas cloud as the Sun, why is the Earth's average composition different from that of the Sun?

Chapter 13 – Discovery of Planets Orbiting other Stars

Sky, universe, all-embracing ether, and immeasurable space alive with movement – all these are of one nature. In space there are countless constellations, suns, and planets; we see only the suns because they give light; the planets remain invisible, for they are small and dark. There are also numberless earths circling around their suns, no worse and no less inhabited than this globe of ours. For no reasonable mind can assume that heavenly bodies which may be far more magnificent than ours would not bear upon them creatures similar or even superior to those upon our human Earth.
-- Giordano Bruno (1548-1600), burned at the stake in 1600 for the heresy of proposing life on other worlds

Chapter Preview

From 1600, when Giordano Bruno was burned at the stake for the heresy of proposing that intelligent life exists on other planets in the Solar System to today, one of the most sought after yet unattainable goals among many scientists is the discovery of life on planets outside our own. Our own Milky Way Galaxy has about 100 billion stars, but until 1995, not one of them exhibited any evidence of being orbited by a planet of any kind. And then the dam broke… In 1997 there are ten sub-star mass planet candidates known to be orbiting other stars. By 2005 100s of planets orbiting other stars will have been confirmed and a spacecraft will have been launched that will examine extrasolar earthlike planets for life. We can only guess at the outcome.

Key Physical Concepts to Understand: *detection of extrasolar planets, Doppler shift of light, brown dwarfs, center of mass of a star system*

II. Introduction

The discovery in the last three years of a handful of planets orbiting stars other than our own promises to transform the field of planetary science from a study of nine planets and their entourage to one of unlimited scope. The field of detection of extrasolar planets has been active for several decades, but has been frustrated by a number of false detections. The first confirmed detection occurred in 1994 when Alexander Wolszczan of Penn State found evidence for planets orbiting a pulsar from the signature wobble that they induced on the pulsar which appeared in its radio signal. But these certainly aren't the life-supporting planets that scientist-explorers have long been searching for. Pulsars are dead stars that are incapable of bathing their planets in life-giving warmth; instead they sterilize them with deadly radiation.

In October 1995, Michel Mayor and Didier Queloz of the Geneva Observatory detected a planet orbiting 51 Pegasi, a star 40 light years away from the Sun (Figure 1). The discovered companion has a mass roughly half that of Jupiter and orbits 51 Pegasi at a distance of only one-eighth that of Mercury's distance from the Sun. This distance would give this planet a blistering 1700 K surface temperature and an orbital period only four days long. Since this discovery 9 other planets have been detected. 1995 was also the year that Bruce Campbell and Gordon Walker, who pioneered the spectroscopic technique used by Mayor and Queloz, gave up after tediously examining 20 stars over a period of a decade. Campbell and Walker were simply unlucky in their choice of stars.

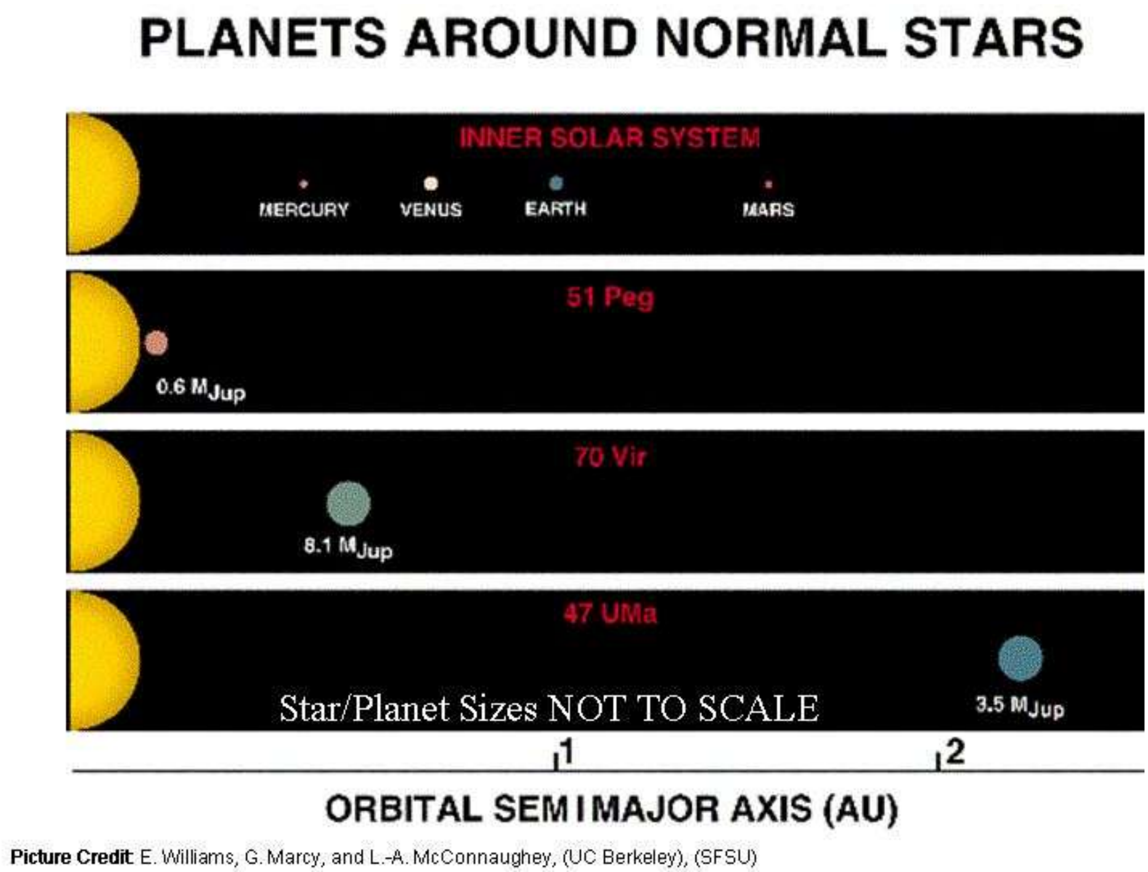


Figure 1. *Properties of extrasolar planets around main sequence stars. This figure compares the estimated sizes and distances of the first-discovered extrasolar planets from their central star relative to the sizes and distances of planets in the inner part of our Solar System. The sizes of planets and stars have been exaggerated with respect to orbital distances.* **Marcy & Butler. FMW 411-20.15.**

Shortly thereafter Marcy and Butler at San Francisco State University confirmed the discovery of the planet circling 51 Pegasi. They have been in the extrasolar planet hunt since 1987, but they were not looking for such a massive planet so close to a central star. They assumed that, like our own Solar System, large planets would be found at a large distance from their central star where ices and volatile gases could condense. In light of the Mayor and Queloz discovery they looked again at their older data. From this data they discovered planets orbiting 70 Virginis, in Virgo, and 47 Ursae Majoris, in the Big Dipper. The planet orbiting 70 Virginis is particularly interesting because it is at the perfect distance to have liquid water, although it is most likely a gas giant. Subsequently Marcy and Butler detected planets around τ Bootis and ρ Cancri. In October of 1996, William Cochran, of the University of Texas and Marcy and Butler independently discovered a planet near 16 Cygni B. There are several hundred solar-like stars within 100 light years of the Sun that are candidates for planetary discovery. Hundreds of extrasolar planets have been discovered to date, and the discovery rate is unlikely to subside in the near future.

Webnote: Known Planetary Systems
www.princeton.edu/~willman/planetary_systems/

The First Extrasolar Planets Discovered in the 1990s

Star	Discoverer	Method of Discovery	Mass of Planet	Distance from Star
51 Pegasi	Mayor & Queloz	spectroscopy	0.5 M_J	0.051 AU
70 Virginis	Marcy & Butler	spectroscopy	6.6 M_J	0.45 AU
47 Ursae Majoris	Marcy & Butler	spectroscopy	2.4 M_J	2.1
τ Bootis	Marcy & Butler	spectroscopy	3.7 M_J	0.047 AU
ρ Cancri	Marcy & Butler	spectroscopy	0.8 M_J	
16 Cygni B	Cochran, Marcy & Butler	spectroscopy	> 1.68 M_J	
Lalande 21185	Gatewood	astrometry	1.5 & 1 M_J	2.5 & 10 AU

III. Dust Disks around Stars and Planetary Systems

Some of the strongest evidence that planetary systems are common among the 100 billion stars making up our galaxy is the discovery of numerous extrasolar circumstellar and protoplanetary disks of gas and dust, made in the last ten years (Figure 2). In some star clusters 60% of the stars manifest evidence of orbiting dust disks, like that out of which our own planets are likely to have formed.

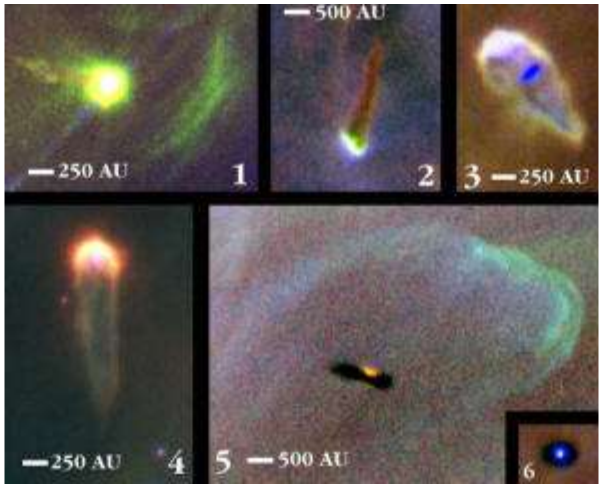


Figure 2. *Dust disks in the Orion Nebula. In this star forming region in the Orion Nebula, disk-shaped objects of collapsing gas and dust are candidates for proto-planetary systems.* ***HST NASA.***

Most dramatic of these discoveries is the optically visible disk of dust around β Pictoris (Figure 3). Pressure from starlight drags individual dust grains and they must spiral into the central star in approximately 10 million years. In order for this massive a dust disk to be maintained it must constantly be restocked by new dust formed from collisions between planetesimals and meteoroids. This provides us indirect evidence of an extrasolar planetary system in formation. Additionally, the dust disk surrounding β Pictoris is warped, possibly caused by the gravitational pull from a gas giant planet at 5AU, suggesting a planet like Jupiter at the same relative distance as Jupiter, and perhaps other planets as well.

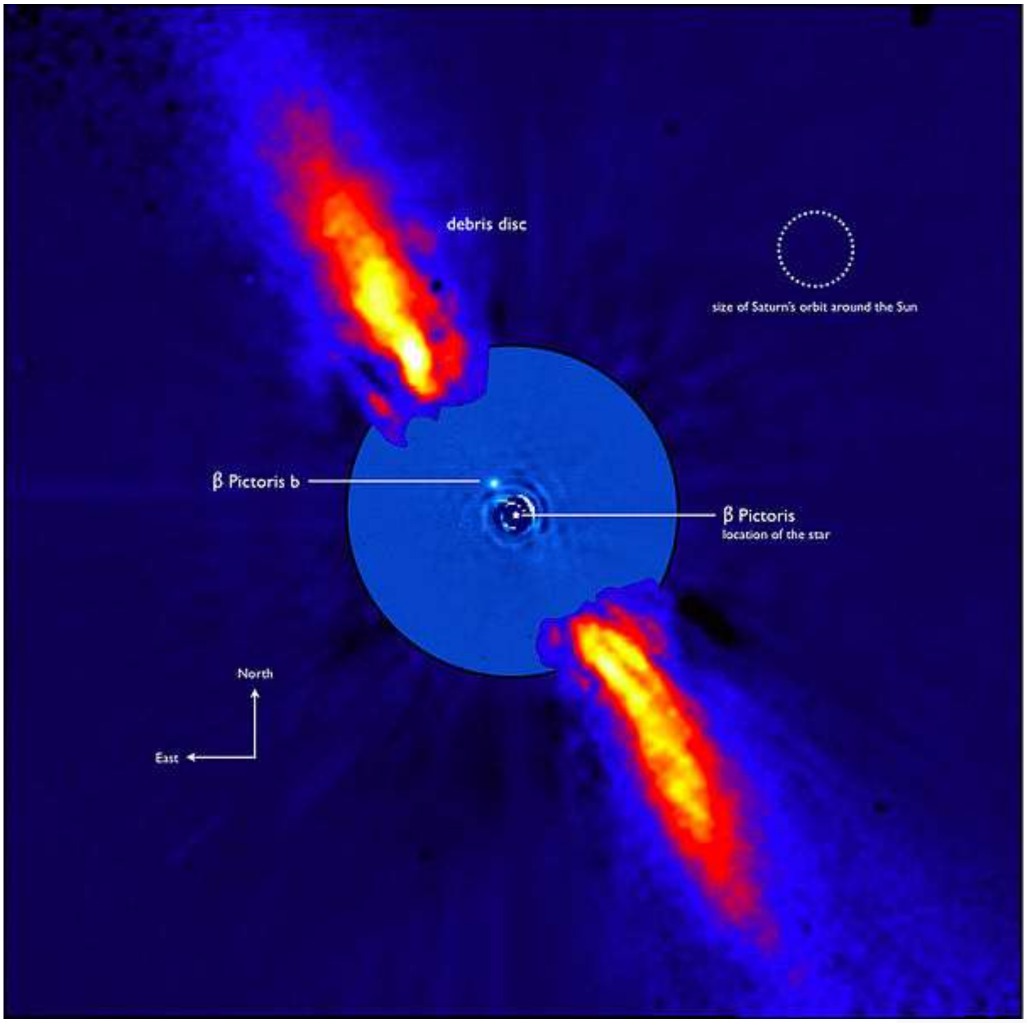


Figure 3. *A protoplanetary dust disk orbiting β Pictoris seen edge-on. "This composite image represents the close environment of Beta Pictoris as seen in near infrared light. This very faint environment is revealed after a very careful subtraction of the much brighter stellar halo. The outer part of the image shows the reflected light on the dust disc, as observed in 1996 with the ADONIS instrument on ESO's 3.6 m telescope; the inner part is the innermost part of the system, as seen at 3.6 microns with NACO on the Very Large Telescope. The newly detected source is more than 1000 times fainter than Beta Pictoris, aligned with the disc, at a projected distance of 8 times the Earth-Sun distance. Both parts of the image were obtained on ESO telescopes equipped with adaptive optics." From http://www.eso.org/public/outreach/press-rel/pr-2008/phot-42-08.html*

Other attempts at detecting protoplanetary dust disks in the early stages of star and planet formation have been successful. About half of all young, solar-type stars show some evidence of disks that could produce planets. Protoplanetary dust disks are normally invisible because the thick disk of dust absorbs all visible light incident on it. However, some protoplanetary dust disks have been seen in silhouette in front of the Orion nebula, a nursery for young stars in the constellation of Orion (Figure 4). These observations support the notion that extrasolar systems are common and provide astronomers with data about the conditions under which they form.

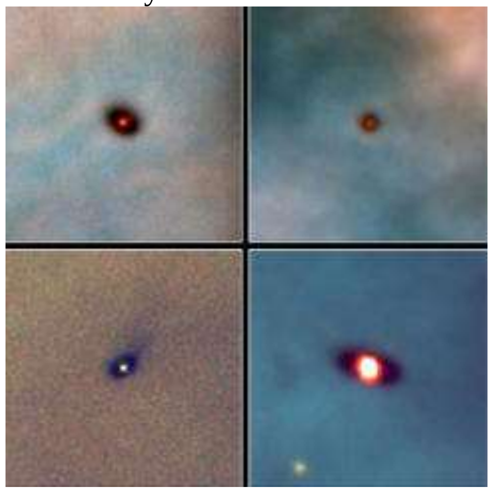


Figure 4. *Protoplanetary dust disks in the Orion seen face-on. These four Hubble Space Telescope images show dust disks around recently formed stars, which are thought to be condensing planets in their dusty envelopes. The dark blobs are silhouetted against the bright background of the Orion Nebula, a cloud of gas and dust illuminated by bright stars. Each of the four disks is more than ten times the diameter of our own Solar System.* ***NASA. FMW 407-20.12.***

A large number of the low-mass companions found in the last few years might not be planets like the planets in our Solar System. Stars are giant masses of gas with enough mass to generate their own energy by thermonuclear fusion. It has been shown theoretically that a mass of gas less than 0.08 times the mass of the Sun is insufficient to ever ignite thermonuclear fusion. The gas giant Jupiter has a mass of approximately 0.001 solar mass. We would certainly regard any body between the mass of the Earth and the mass of Jupiter as a planet, but what about bodies in the gap between 0.001 and 0.08 solar masses, which includes some of the recently discovered planets?

Astronomers designate objects in the range 0.001 to 0.08 solar masses as planets, only if they form in the same way that planets in our own Solar System formed, that is, after the formation of the central star. Objects in this intermediate mass range are called **brown dwarfs** (Figure 5, because they would be faint and small) if they formed *at they same time* as the central star they are orbiting. What is the purpose of this rather hairsplitting differentiation? Only this: if a stellar pair forms (e.g. a solar type star and a brown dwarf companion) together out of a collapsing gas cloud, gravitational forces from the two are predicted to keep any planets from subsequently forming in the system; planetesimals are either absorbed by the two stars or ejected from the system. If we are interested in finding planetary systems including Earth-like planets that have the potential for harboring life, we need not examine systems with brown dwarf companions. Planets are only expected to form in a dust disk surrounding a fully formed single star. So it is important to differentiate between star systems with a massive gas giant planet and those with a brown dwarf companion. What the mass dividing line is, or even is there is one, between gas giants and brown dwarfs is unknown.

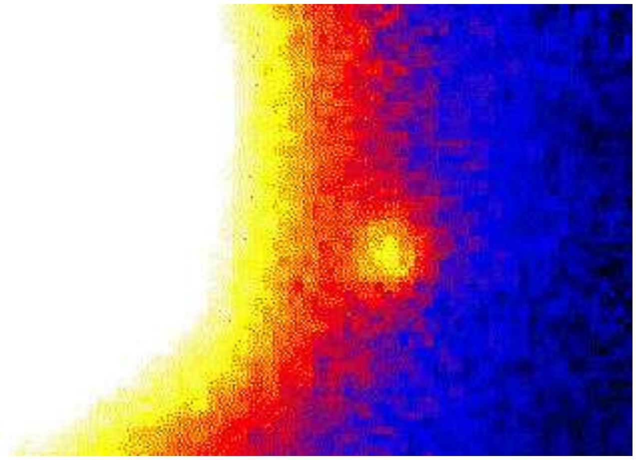


Figure 5. *GL 229B a rarely seen brown dwarf. The faint star seen to the right of the overexposed image of its bright companion is the elusive brown dwarf, a star with too little mass to fuse hydrogen, but massive enough to form at the same time as its companion.* **Palomar.**

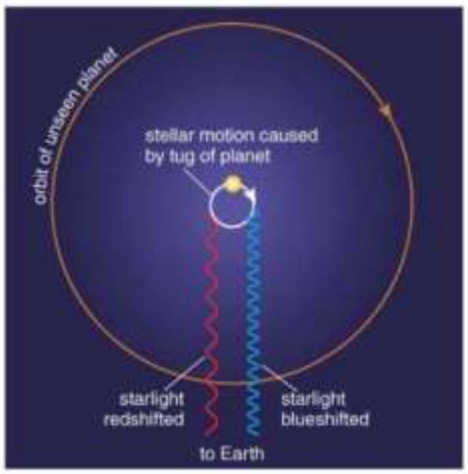
"If a new object orbiting a star is a gas-giant like Jupiter," Alan Boss of California Institute of Technology wrote in Physics Today "then in analogy with our own solar system, we would expect that earthlike planets also formed around that star. However, if a new object is a brown dwarf star, then it is unclear whether or not earthlike planets also formed – binary stars are thought to disrupt the planet formation process."

Some contend that is premature to regard 51 Pegasi and 70 Virginis, in particular, as planets. They should have more circular orbits farther out, as in our Solar System, in order that ices and volatile gases could have condensed to form them. However, they could have migrated into the inner parts of their respective planetary systems *after* they formed. If, for example, sufficient friction were exerted on young planets by a protoplanetary dust disk, they would spiral in toward the central star. In any case, the only direct confirmation that a planetary system can really harbor an Earth-like planet is to directly detect an Earth-like planet. Such detection will be a major accomplishment of astronomy in our lifetimes.

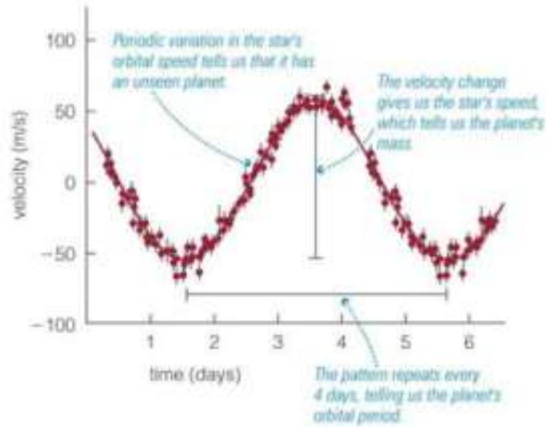
IV. Techniques

Extrasolar planets and brown dwarfs can be detected directly or indirectly. Detections by imaging planets directly are extremely difficult. The Sun is 10^9 times brighter than Jupiter at visible wavelengths of light, and 10^{10} times brighter than Earth. At thermal infrared wavelengths, longer than 10 microns, the Sun is more luminous than planets by 10^4 to 10^6. This makes infrared wavelengths the region of choice for detecting planets. Another difficulty in the planet detection game is that the nearness of planets to their central star combined with the blurring effect of the Earth's atmosphere on images makes direct detection from Earth almost impossible. New generation telescopes with sophisticated optics can be used to remove effects of the Earth's atmosphere; space-based telescopes like the Hubble Space Telescope will play a significant role in detecting and studying extrasolar planets.

Astronomers currently use two different indirect techniques to detect extrasolar planets, **spectroscopy** and **astrometry**. In the spectroscopy technique astronomers look for the change in velocity of the star due to a massive planet circling around it (Figure 6). Like a person trying to walk and swing a bucketful of water around their head at the same time, a star being orbited by a massive planet will wobble as it moves through space. Strictly speaking the star *and* the massive planet both orbit their **center of mass**.



a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



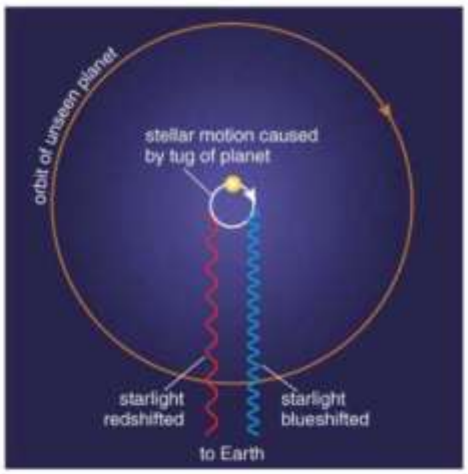
b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

Figure 6. *The motion of an unseen planet and its mother star about their common center of mass detected from the cyclic redshift-then-blueshift of the lines in the spectrum of the brighter star. As the star moves towards us in its orbit, its spectral lines will appear blueshifted; as it moves away its lines will appear redshifted.* **From www.lasp.colorado.edu**

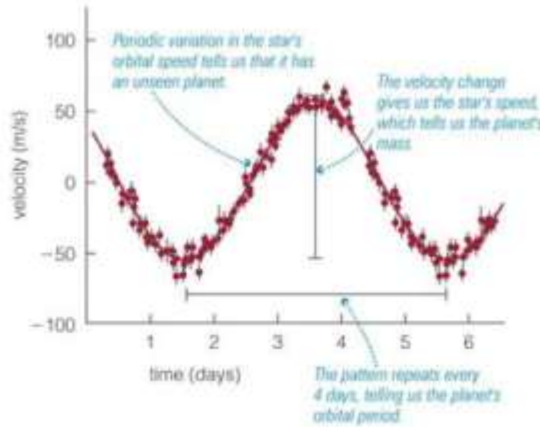
WebNote: Marcy and Butler Doppler example.

Detection of a Planetary System from a Star's Wobble about the Center of Mass

This happens with the Sun and Jupiter as well. To determine where the center of mass of the Sun-Jupiter system is, imagine balancing the Sun on a giant seesaw, with their current separation of 5 AU maintained (Figure 7). Jupiter would have to maintain a greater distance from the seesaw fulcrum than the Sun in order to maintain a balance. In fact distance of each from the fulcrum is in inverse proportion to its mass. The fulcrum is simply the position of the center of mass for the Sun-Jupiter system, the point at which their masses would balance. When Jupiter orbits, it is orbiting the center of mass of the Solar System, which is close to the center of mass to the Sun-Jupiter system, since the other planets have too little mass to have a significant effect. The Sun also orbits the center of mass. The Sun is so massive when compared to Jupiter that the Sun-Jupiter center of mass is actually slightly interior to the Sun's surface. To an outside observer, however, the Sun would appear to move in a circular orbit with a velocity of 13.1 km/s and a 12-year period – the orbital period of Jupiter.)



a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



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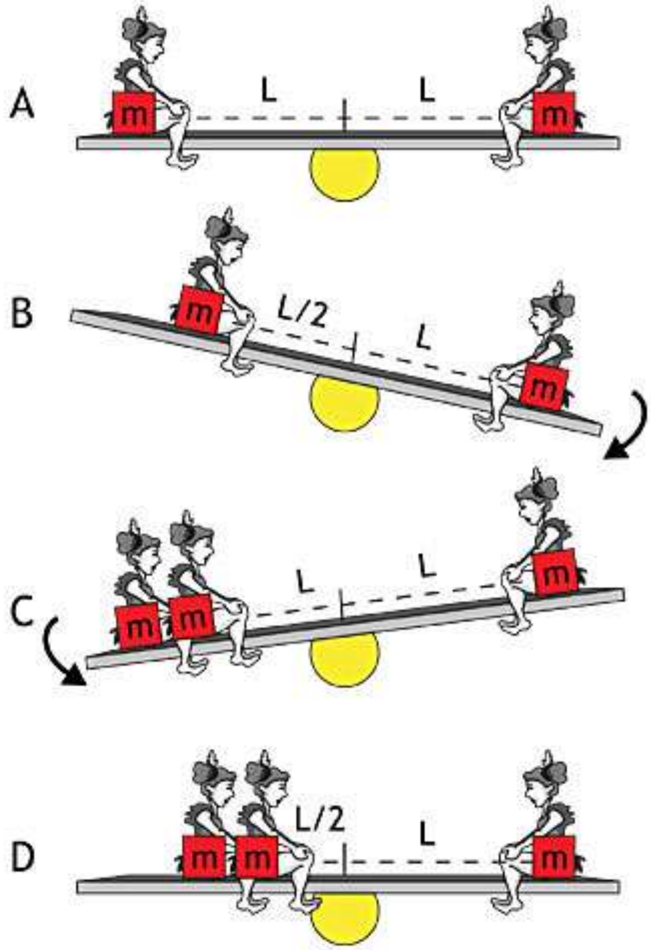

Figure 7. *The analogy between a seesaws and a planet orbiting a star. The result of an unbalanced seesaw is that the center of mass moves toward the side with the most mass. The same result is seen in a planet orbiting a star. The pair are actually both orbiting their center of mass, but that center of mass is much closer to the more massive star than the less massive planet. From http://www.pbs.org/opb/circus/classroom/circus-physics/center-mass/*

A. Spectroscopic Technique

WebVideo: Kepler Results http://www.youtube.com/watch?v=1-0-HKHjsPY

Webanimation: Binary Star Browser
http://instruct1.cit.cornell.edu/~tlh10/java/binary/binary.htm

One way of measuring the presence of an unseen planet around a star is to look for a periodic change in the measured velocity of that star. The star's velocity can be measured by precisely determining the wavelengths of sharp absorption features in its spectra. These features are shifted to the red if the star has a velocity away from us and are shifted to the blue if the star has a velocity toward us. This shift in wavelength of light was first explained by the Austrian physicist Christian Doppler in 1842, and demonstrated by moving a brass band on a railroad flat car away from and toward observers (or in this case, listeners). You have most likely experienced **Doppler shift** yourself – a passing ambulance with siren blaring drops in pitch as it passes you, going from sound waves of higher pitch and shorter wavelength as it approaches to waves of lower pitch and longer wavelength as it recedes (this is explained by the wave nature of light and sound as illustrated in Figure 8). By monitoring a star for a cyclic change in Doppler wavelength shift in its spectrum, the effects of an unseen massive, orbiting planet can be detected. This technique does not work for a planetary system seen face-on as there is no component of velocity toward or away from the observer; it works best for a planetary system seen edge-on. With the spectroscopic technique it is easiest to pick out short-period planets, like the companion to 51 Pegasi with a 4-day period (Figure 9). Picking out a planet with a 12-year period, like Jupiter would take over a decade of patient observation.

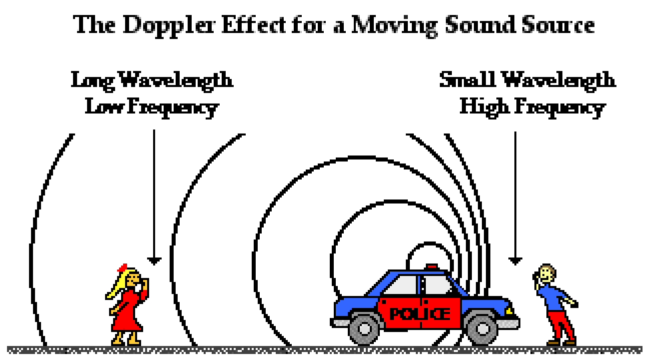

Figure 8. *Doppler shift of waves (either sound or light) can be illustrated with a police car siren. As the speeding police car approaches a pedestrian the sound waves are compressed in wavelength, resulting in a higher pitch. Receding from pedestrian waves are decompressed, resulting in sound of a lower pitch. As the car passes a pedestrian the pitch drops dramatically.* **From physicsclassroom.com.**

WebVideo: Doppler Shift
http://www.youtube.com/watch?v=Djz_rtnXSfY

WebAnimations: Doppler Shift
http://en.wikipedia.org/wiki/Doppler_effect

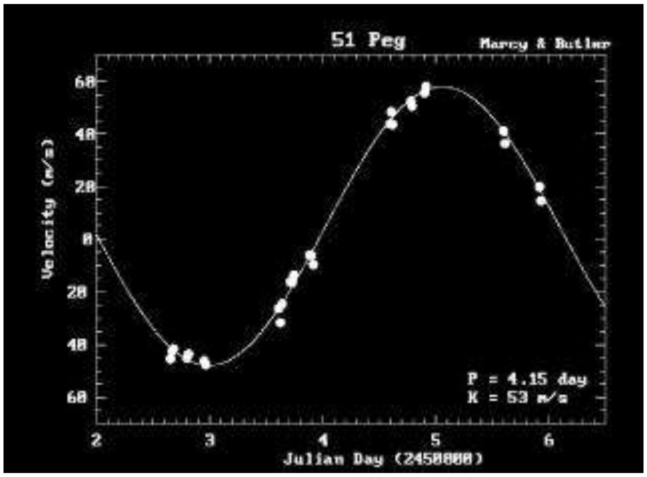

Figure 9. *The changing velocity of 51 Pegasus due to the gravitational influence of an unseen planet. Each data point represents a single Doppler shift velocity measurement of 51 Peg from as determined from the measured wavelengths of absorption lines in its spectrum. Velocities vary in a smooth curve over the 4.231-day orbital period of the companion. The period is labeled on the horizontal axis as the phase of the period, ranging from 0.0 to 1.0. From www.teachastronomy.com/astropediaimages/gasretention.jpg*

B. Astrometric Technique

In the astrometric method, astronomers directly detect the wobble of a star relative to other stars in the sky. It is possible to detect the wiggle of a star about its center of mass to one-thousandth of an arcsecond or better. Unlike the spectroscopic method it is easiest to detect planets with long period orbits, far from their central star. It takes many years to confirm the discovery by following the planet over an orbital period.

In 1996 George Gatewood of Allegheny Observatory reported his dissection of 50 years of astrometric data of the star Lalande 21185 data and discovered a Jupiter-sized planet in 5.8-year orbit at 2 AU. The data also yield evidence of a second planet in a 30-year orbit at 10 AU, the first discovery of a star system, outside our own, with more than one planet. Some argue that Lalande 21185 represents the only real planet discoveries and that previous discoveries with the spectroscopic technique were of brown dwarf companions.

V. The Existence of Intelligent Life

Any individual detection of a planet does not in itself mean that extraterrestrial life has been detected. It is very unlikely to have intelligent life on any single *Earth-like* planet. The planets that have been discovered to date are unlike those in our solar system, in terms of mass and distance from their central star; their other properties are completely unknown. But each detection certainly ups the probability of extraterrestrial life.

The frequency of Earth-like planets in our galaxy can't even be well estimated, since we know of only one instance where a system has been adequately examined. Star formation theory is well developed as a result of an enormous amount of observational data. Although planet formation theory is highly sophisticated but only constrained by one instance, the Earth. Extrapolating this theory to predict the frequency of occurrence of life-supporting planets is really little more than educated guessing. This provides strong motivation for the attempted detection of extrasolar Earth-like planets.

VI. Current and Future Spacecraft Missions

One of NASA's highest priorities is the detection of Earth-like bodies orbiting other stars and examining them for evidence of life. Several have been proposed for launch within the next decade. The first, Kepler, launched in 2009, is detecting hundreds of planets as they pass in front of their central star, dimming the starlight slightly but measurably. Its proponents argue that it could detect some 2,400 new planets, some of which would have the Earth's size and solid surface. Even a planet of the Earth's size and distance of 1 AU from its central star would be detectable. Two other NASA mission plans are more complex. The first would launch an infrared telescope capable not only of detecting a planet from its infrared radiation, but measuring the carbon dioxide, water, and ozone on a planet from its infrared signature. The latter would provide evidence for life on a planet, at least life as we know it on Earth. The second would launch an array of small telescopes that image in unison, acting as one huge telescope that would be able to image nearby planetary systems to the resolution required to detect Earth-like planets. The field of study of extrasolar planets is exploding.

Summary

One of the most important discoveries in the last few years is the detection of extrasolar Jupiter-like planets. Planets can be confused with brown dwarfs, low-mass objects that form with a star at the same time the star forms, preventing the subsequent formation of planets. In the speculation concerning the existence of life in any star system other than our own, it is essential to determine the probability of finding extrasolar Earth-like planets capable of supporting life. Although these planets can not be seen directly, their gravitational effects can be measured by measuring the wobble of the star that they orbit, either directly or through the stars Doppler shift. It is also possible that they can be seen as they pass in front of their star, causing a slight drop in observed stellar brightness.

Key Words & Phrases

1. **Astrometry –** the measurement of the position of a star, or other celestial body
2. **Brown dwarfs -** objects between planets and hydrogen fusing stars in mass. Brown dwarfs will never become self-luminous due to thermonuclear fusion, like other stars, but they form at they same time as the central star they are orbiting, unlike planets.
3. **Center of mass –** the point on which an object can be balanced
4. **Doppler shift** – the apparent shift in the wavelength of sound or light in a moving source. As a light source moves with a velocity toward the observer the wavelength

of its emission appears shifted to the red, or red-shifted. As a light source moves with a velocity away from the observer the wavelength of its emission appears shifted to the blue, or blue-shifted.

Review for Understanding

1. Describe the methods for detecting invisible planets orbiting stars.
2. What is a brown dwarf and why is it classified as a star?
3. Summarize the evidence that extrasolar planets are common among stars in our galaxy.
4. What is Doppler shift?
5. Why is it difficult to detect extrasolar planets directly?
6. Define center of mass in your own words.

Essay Questions

1. What is the scientific importance of discovering an extrasolar Earth-like planet?
2. What types of planetary systems are best detected by astrometry and which are best detected by spectroscopy?
3. Make a model of a scale model of planetary system having a 1 solar mass star and a Jupiter-sized planet at 1 AU using balls, fruits, or household objects. What were the sizes of the objects and how far away did you place them? Where would the center of mass of this system be?