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Planetary Formation

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"Planetary Formation"

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Stephanie Blackmon

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requirements for completion of the
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meets the criteria for acceptance
and has been approved by the undersigned readers

Thesis Director

Second Reader

Third Reader

Director of the Carl Goodson Honors Program

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Chapter 1
The Creation

Current theory indicates that somewhere between 13 and 18 billion years ago, the creation of our universe began. The name given to this event is "The Big Bang." At some time in the next 10 million years, the galaxy we now call the Milky Way was created. In the ensuing five billion years, our solar system came into being. There was not much between the stars in our corner of the galaxy five billion years ago. It was a virtual vacuum. The air we breathe today has an average of 30 million trillion (30×10^{18}) atoms per cubic centimeter; five billion years ago the near vacuum of the interstellar cloud contained approximately 12 atoms per cubic centimeter. It was also very cold five billion years ago. The temperature in the interstellar cloud was less than 50 degrees Kelvin. For a comparison, consider that water freezes at 273 degrees Kelvin and room temperature is usually around 300 degrees Kelvin (Kaufmann, Planets 4).

This interstellar cloud, made of sparse atoms, was composed mostly of hydrogen and helium. In fact, over 95% of it was hydrogen and helium. The rest of the cloud consisted of heavy elements such as silicon, magnesium, aluminum and iron which existed as microscopic dust particles only one micrometer (1×10^{-6} m) in size. It also consisted of organic molecules oxygen, carbon, and nitrogen. These heavy materials were probably the result of nuclear reactions inside of earlier stars (Kaufmann, Planets 4).

The formation of our solar system was initiated by a compression of the interstellar cloud. Before this compression, the interstellar cloud was in equilibrium. The gas pressure inside the cloud was equal to the force of gravity outside the cloud. Had the gas pressure inside the cloud been greater than the gravity outside the cloud, it would have expanded. Conversely, if the gravity outside the cloud had been greater than the gas pressure inside of the cloud, it would have contracted (Kaufmann, Planets 6).

There are two theories as to what caused the compression of the interstellar cloud so our Sun, a star, could form. According to the first theory, "A spiral arm of our galaxy passed through our region of space some five billion years ago. This would have caused a slight compression of the interstellar cloud, and star creation could have begun" (Kaufmann, Planets 6). One reason this theory has substance is that astronomers have found many developing stars and gas clouds in the arms of other spiral galaxies (Kaufmann, Planets 6).

According to the second theory, a massive star close to us became a supernova. The shock wave resulting from the massive explosion caused our interstellar cloud to compress and the creation of the Sun began. Scientists have found evidence which helps to substantiate this theory. They have discovered important elements in meteorites in our solar system which would have been present in a supernova explosion (Kaufmann, Planets 6).

Regardless of what caused the compression, once it began, the dust grains in the interstellar cloud drew closer. At this point, there were approximately 10,000 grains per cubic kilometer. This was almost a one-hundred-fold increase. Since the dust grains were so much closer, heat and light from nearby stars could not shine through the dust. Thus the temperature inside the cloud dropped much closer to absolute zero (0 degrees Kelvin, -273 degrees Celsius). Along with the decrease in temperature came a decrease in gas pressure inside the cloud. This decrease in inner pressure caused the cloud to contract. Eddies and whirlpools formed and divided the huge interstellar cloud into smaller pieces--enough pieces to create several solar systems. One of these pieces eventually became our solar system (Kaufmann, Planets 9).

With the continuing contraction, the cloud began to rotate faster and faster. This caused it to fragment into a disk called a Primordial Solar Nebula. The nebula was about 10 billion kilometers across (approximately the size of Neptune's orbit around the Sun), 200 million kilometers thick (approximately the distance between the Earth and the Sun), and contained two times as much matter as is present in the solar system today (Kaufmann, Planets 9).

After 50 million years, the primordial solar nebula was completely formed, but its evolution was not complete. At this time, there were three types of materials present in the solar nebula (Kaufmann, Planets 11).

Rock: Different combinations of silicates, oxides of metals, silicon, magnesium, aluminum and iron. These materials have melting/boiling points in the thousands of degrees Kelvin (Kaufmann, Planets 11).

Liquids and Ices: Different chemical combinations of carbon, nitrogen, hydrogen and oxygen. Combinations like water, carbon dioxide, methane and ammonia. These materials have melting/boiling points in the 100 to 300 degrees Kelvin (-173 to 27 degrees Celsius) range (Kaufmann, Planets 11).

Gases: Hydrogen, Helium, Neon and Argon all in their pure forms. These elements remain in gaseous form except when they reach temperatures near absolute zero (Kaufmann, Planets 11).

Material was continually being contracted to the center of the nebula, and this caused a protosun to be formed. During the formation of the protosun, vast amounts of matter were drawn to the center of the primordial solar nebula. Nuclear reactions began and an icy substance within the matter was vaporized. This signified the birth of the protosun (Kaufmann, Planets 10, 11).

Once the protosun had been formed, its magnetic field played an important role in the formation of the rest of the solar system. First, due to the protosun's magnetic field, the protosun was able to maintain contact with the gases in the nebula. This meant that the protosun was able to sustain a slow rate of rotation. It completed one rotation once every four weeks (Kaufmann, Planets 11).

Second, the dragging of the protosun's magnetic field caused a break up of the solar nebula. This meant that the rotation of the solar nebula was spread more evenly through the forming solar system instead of being concentrated on the protosun. This rotation spread from the inner solar nebula to the outer solar nebula and lasted only a few thousand years. Once the rotation had passed completely from inner to outer solar nebula, the planets formed (Kaufmann, Planets 11).

After the protosun formed, the temperatures in the solar nebula began to drop and materials began to solidify. Because the temperatures near the protosun were still very high, only rocky substances such as iron, silicates, and oxides of metals were able to solidify there. In regions farther away from the protosun, the temperatures were cooler and this allowed thin layers of ice to cover the dust grains. The farther from the protosun, the cooler the temperatures and, therefore, the thicker the layers of ice covering the dust grains. The ice was made of water ice, dry ice and frozen ammonia and methane. All of the dust particles in the solar nebula, both near to and far from the protosun, were embedded in a cloud of hydrogen and helium (Kaufmann, Planets 12).

During this time period, the dust grains were probably fluffy. After collisions they stuck to each other. After a few hundred thousand years the dust grains were no longer microscopic. Instead, they had formed clumps a few millimeters or centimeters in diameter. Due to gravity, these clumps of dust gradually began to settle toward the mid-plane of the solar nebula. This meant that most of the solar nebula's solid material was now settled in a sheet with the protosun at its center (Kaufmann, Planets 12).

Once again, gravity came into play. It caused the sheet of tiny clumps to become unstable. This caused the clumps to accrete to areas which were more populated with clumps and eventually, over a long period of time, the clumps became planetesimals. The size of these planetesimals ranged from under one meter to about 100 kilometers in diameter (Broadhurst 40).

The chemical composition of each of the planetesimals was not the same. Near the protosun the planetesimals were made almost completely of rocky materials which were able to exist under high temperatures. Farther from the protosun, where it was cooler, the planetesimals included water ice in their composition. Even further away from the protosun, where the temperatures were much colder, the planetesimals also included forms of frozen methane and ammonia (Smith and Terrile).

Over the next few million years, the planetesimals continued to accrete, and eventually eight protoplanets formed. These protoplanets were to become Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune. There are many theories as to how Pluto formed. These will be discussed later. Beyond these planets, scientists believe a cloud of cold material continued to orbit the protosun. This cloud, however, is too dark and distant for astronomers to see (Smith and Terrile).

The four protoplanets, in order from closest to farthest from the protosun were Mercury, Venus, Earth and Mars. In these four protoplanets, the decay of their radioactive isotopes caused their centers to melt. Because of gravity, the heavier materials in these protoplanets sunk to the centers and caused the lighter materials to be pushed to the surfaces of the protoplanets (Kaufmann, Planets 13).

Due to the heat of the protosun and Mercury's low gravity, the gases in Mercury boiled off, and Mercury was left with no atmosphere. Mars also lost most of its gaseous atmosphere for the same reasons. However, it did retain a thin layer of carbon dioxide as an atmosphere. Venus and Earth, on the other hand, had strong enough gravity to retain their gaseous atmospheres. Their atmospheres were scanty and lay lower than ten kilometers above their surfaces (Kaufmann, Planets 14, 15).

The chemical composition of these four protoplanets also played an important role in the make-up of their existent, or nonexistent, atmospheres. Mercury, Venus, Earth and Mars are made of mostly rocky substances due to their proximity to the protosun and the resulting heat from it. In the forming of these protoplanets, most of the liquids and gases they had were vaporized or boiled off by the Sun (Kaufmann, Planets 13, 14).

The inner core of each of these protoplanets also depended greatly on the primordial dust grains which made them. All four inner protoplanets had molten iron cores and mantles made of less dense molten rock material. Mercury had the largest iron core of the four protoplanets. It made up 80% percent of Mercury's mass and was three-quarters of the radius of the protoplanet from center to surface. The iron cores of Venus and Earth were only one-half of the radius of the protoplanet; Mars's core was even smaller (Kaufmann, Planets 15).

From studies of the chemical properties of the rocky material in the early solar nebula, we know that iron, nickel, and oxides of other metals had to be the first to condense from the hot inner part of the solar nebula because they have the highest condensation temperatures. Silicates and other rock-forming materials which made up the protoplanets have slightly lower condensation temperatures. This tells us that the grains which condensed closest to the protosun had to have a higher iron content than those which condensed further from the protosun. That is why Mercury has a higher iron content than any other planet in the solar system (Kaufmann, Planets 15, 16).

The outer protoplanets contained more ice, liquids, ammonia and methane than the four inner planets. This explains why they have atmospheres which are tens of thousand of kilometers thick. This is much thicker than any of the atmospheres of the four inner planets. It also explains why the outer planets have atmospheres containing methane and ammonia rather than carbon dioxide like the inner planets (Kaufmann, Planets 16).

Jupiter and Saturn had very strong gravitational fields. Their gravitational fields were strong enough to pull tremendous amounts of hydrogen and helium into their atmospheres, as well as methane and ammonia. Since Jupiter and Saturn had such strong gravitational fields and were so far from the heat of the protosun, they were able to retain all of their gases. Their gravity was also strong enough to pull several satellites into orbit around each of them (Kaufmann, Planets 16).

Uranus and Neptune also captured several satellites. But their gravity was not strong enough to retain all of their original hydrogen and helium. Therefore, their atmospheres were more rich in ammonia and methane and less rich in hydrogen and helium than those of Jupiter and Saturn (Kaufmann, Planets 16).

The evolution of the solar nebula did not stop with the protoplanets; the protosun also continued to evolve. For over 4.5 billion years, the continuing inward pressure of trillions and trillions of tons of gas caused the protosun to grow hotter and hotter on the inside, and finally so hot that thermonuclear fires began to ignite. The thermonuclear fires started as a result of the fusing of hydrogen atoms to produce helium atoms at temperatures of millions of degrees. These fires signified the birth of our Sun (Smith and Terrile).

Part of the evolution of a star is the continuous emission of electrons and protons as a result of the thermonuclear fires in the star's core. Following the onset of thermonuclear reactions, the intensity of these emissions was unusually high and resulted in what are called T Tauri winds. Over a period of approximately one million years, our solar system was blasted by the powerful T Tauri winds coming from our Sun. Prior to these winds, our solar system contained enough hydrogen, helium and matter to create two suns. The T Tauri winds, however, blasted away any gases or star dust which had not yet become planetesimals. Another result of the tremendous winds was that the planetesimals lost their primordial atmospheres. The only things to stay were the planetesimals themselves, their satellites, the asteroids, the meteoroids and the Sun. The T Tauri winds also signified the end of the final stage of the creation of the planets (Gore 20).

After the T Tauri winds, the planets continued to evolve. Over a period of 700 million years, Jupiter, the largest planet in our solar system, played the role of a slingshot as its gravity caused planetesimals to be deflected toward the inner regions of the solar system and thrown into unpredictable orbits. Many of these planetesimals, some even larger than the Earth's moon, were cleared from the solar system as a result of their erratic orbits or collisions. Through bombardment, some of these objects may have caused the numerous craters on Mercury, Venus, Earth and Mars and many of their satellites (Gore 28).

During this period, Jupiter's immense size and gravitational field had another effect on our developing solar system. Jupiter's gravitational field was so strong that it probably caused the planetesimals in the asteroid belt between Mars and Jupiter to remain fragmented. Had Jupiter's gravitational field been weaker, the asteroid belt might have become a planet (Gore 28).

Uranus and Neptune also played important roles in the development of the solar system at this time. The huge cloud of icy comets orbiting the Sun on the outer edge of the solar system is thought to be the result of Uranus and Neptune's gravity throwing planetesimals outward. The icy planetesimals they threw toward the inner regions of the solar system are thought to have been directed by Jupiter's gravitational field. These redirected projectiles bombarded the four inner planets and cratered their surfaces. They may have also been responsible for providing the inner planets with water. Earth is thought to have been left with several times the amount of water present today. The comets are also thought to have been responsible for the present atmospheres on the inner planets (Gore 28).

After the occurrence of the tremendous T Tauri winds, most of the matter in the solar system was contained in the Sun as it is today (Kaufmann, Planets 21). Presently, the Sun holds 99.80% of the matter in the solar system. The remaining 0.20% of the matter in the solar system is distributed as follows: 0.14% of the matter is in the planets, 0.05% is in the comets, 0.00005% is in all of the satellites and rings, 0.000002% is in the asteroids, and 0.0000001% is dust and debris (Abell, Morrison, and Wolf 170). From these figures, one might conclude that the planets of our solar system are only "microscopic impurities in the vast cosmic vacuum that surrounds our star" (Kaufmann, Planets 21). To get an idea of the size of the solar system, imagine that "If the Sun were reduced to the size of a basketball, the Earth would be an apple-seed some 30 yards from the ball. Jupiter would be a golf ball 150 yards away, and tiny Pluto, which is usually the outermost planet, would be a dust mote almost three quarters of a mile from the center" (A.S.P.: An Armchair Tour).

Astronomers have long believed that the inner, rocky planets were created from the collision of tiny dust particles. The dust particles grew to become small rocks. These small rocks continued to collide with other rocks and eventually became larger rocks. Through continuing collisions, these rocks eventually became large moon-like planetesimals. The collisions continued, and the planetesimals became the rocky inner planets we know today. Physicist David Peak at Union College in Schenectady, New York, is one of a number of scientists who propose an alternative theory (Daviss 114).

According to Peak, this long held theory requires some kind of "magical interaction between pebbles that existed billions of years ago and doesn't exist now" (Daviss 114). He believes that the protoplanets were not small condensed objects, but rather had very low density and were made up of dust and ice. The key to this theory is its assertion that the aggregates were of very low density. If their density had been high, then the aggregates would not have collided and stuck to the object they impacted. Instead, they would have acted like asteroids and become locked into orbits. If aggregates had been low density balls of fluff, then they would have floated like dandelion seeds and with each collision, would have grown. When each fluffy, low density dust aggregate grew to an appreciable size, it would condense due to its own gravitational force. Then, because of the compression, the aggregate would have a much greater density (Daviss 114-116).

Another factor included with this alternative theory which would tend to increase the density is the possible role of radioactive isotopes in the dust balls. In the really large balls, radioactive decay may have taken place in their interiors and caused the dust balls to melt and then recrystallize in the form of rock (Daviss 116).

One more mechanism which might account for the high density of the rocky inner planets is the impact of comets and asteroids. These would press the loose materials of the dust balls into denser wads. The collisions would also have created heat as the kinetic energy from the collision was transferred to heat energy. This heat could cause the dust to melt and recrystallize as rock at the point of contact with the colliding comet or asteroid (Daviss 116).

Unfortunately, this theory has one large hole in it. According to the theory, the time it would take for a dust ball to coalesce into a planet would be much longer than the estimated time it took for our solar system to form. However, this theory may possibly be applicable to the formation of planets orbiting other stars (Daviss 116).

Chapter 2
Mercury

On November 3, 1973, The Mariner 10 spacecraft was launched from the Kennedy Space Center in Florida. Its primary objective was to obtain close-up views of Mercury. Before Mariner 10 was launched, it was virtually impossible to see Mercury because of its close proximity to the Sun. (Mercury orbits the Sun at a distance of 0.3871 AU.) The solar glare from the Sun obstructed astronomers' views of the tiny planet. The haze and dust at sunrise and sunset made detailed telescopic observations of Mercury hopeless. But on March 29, 1974, Mariner 10 got to within 703 kilometers of Mercury. From that encounter much was learned about our solar system's inner-most planet (NASA: Our Solar System 8; Arny A-27).

Mariner 10 showed us that Mercury has a very thin atmosphere composed mostly of argon, neon and helium. Its atmosphere is about one-trillionth the density of Earth's atmosphere (NASA: Our Solar System 8).

Data returned from the Mariner 10 also made it possible for scientists to determine that Mercury's core is made of iron. This was inferred from the observation of Mercury's magnetic field. Only an iron core could support a permanent, planet-wide magnetic field (Kaufmann, Planets 31).

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Although Mercury's magnetic field is 100 times smaller than Earth's magnetic field, it does not have the weakest magnetic field in the solar system. Of the four inner planets, Mars and Venus have much weaker magnetic fields than Mercury (Kaufmann, Planets 31).

With a diameter of 4,880 kilometers, Mercury is the second smallest planet in our solar system. Scientists have calculated that Mercury's iron core has an approximate diameter of 3,600 kilometers. That means that Mercury's rock mantle is only about 640 kilometers thick. For a comparison, consider that the Earth's moon also has an approximate diameter of 3,600 kilometers. Thus, Mercury's core is the same size as Earth's moon and, therefore, Mercury itself is only marginally larger (Kaufmann, Planets 31). Mercury's crust is thought to be made of light silicate rock similar to Earth's crust (NASA: Our Solar System 8).

In 1889, Giovanni Schiaparelli proposed that Mercury rotated only once during one complete revolution about the Sun, thus implying that only one side of Mercury would experience the blistering heat of the Sun, while the opposite side of Mercury would experience extreme cold. This theory was disproved by the research of Rolf Dyce and Gordon Pettingill in 1965. Using the Arecibo radio telescope in Puerto Rico, they determined that Mercury makes one complete rotation over a period of 59 days. In other words, during the 88 days it takes for Mercury to orbit the Sun, all sides of Mercury are exposed to the face of the Sun at one time or another (NASA: Our Solar System 8).

When close to the Sun, the temperatures on the surface of

It is thought that somewhere between three and four billion years ago a large asteroid, perhaps the largest one ever to strike Mercury, landed at the point now called the Caloris Basin. Astronomers believe that the asteroid hit Mercury so hard that it broke through Mercury's crust and caused lava to well up and pour onto the surface of Mercury. The impact was so cataclysmic that it caused unusual ripples on the opposite side of Mercury. Scientists have theorized that a tremendous shaking effect from the asteroid's impact caused immense seismic waves, which travelled through the planet. They believe that the unique ripples at the region on the opposite side of the Caloris Basin were a result of these seismic waves (Kaufmann, Planets 37-39).

Unfortunately, we still know relatively little about Mercury. Mariner 10 has helped us to learn a number of things about Mercury, but it has only given us information about half of this planet. With each flyby of the now defunct Mariner 10 spacecraft, all of the pictures and data received deals with the same side of Mercury. No other space crafts have ventured near Mercury since the launching of Mariner 10 (NASA: Our Solar System 8).

Chapter 3
Venus

Our sister planet, Venus, resides 108 million kilometers from the Sun (0.7233 AU). From Earth, Venus is seen by the naked eye as a bright morning or evening "star" due to the thick layer of yellowish-white clouds. This layer of clouds is the Venusian atmosphere. It consists almost completely of carbon dioxide and the pressure it exerts on the surface of Venus is about 90 times as strong as the pressure on the surface of the Earth. That is about as strong as the pressure 3,000 feet deep in an ocean on the Earth (Kaufmann, Planets 44, 52; Arny A-27).

Thirty-five kilometers above the Venusian surface is where Venus' atmosphere begins. It is approximately 30 kilometers thick, and at the cloud tops, 65 kilometers above the Venusian surface, the temperature averages about 223 degrees Kelvin (-50 degrees Celsius). The surface of Venus, however, is even hotter than Mercury at noon due to a greenhouse effect. On average, the Venusian surface temperature reaches as high as 755 degrees Kelvin (482 degrees Celsius). This temperature is about 45 degrees hotter than noon on Mercury, which is closer to the Sun. During the night, the cloud cover over Venus retains much of Venus' daytime heat. Venus' surface remains so hot that rocks glow red during the night (Kaufmann, Planets 52).

The Venusian atmosphere travels in a retrograde motion and makes one complete rotation around Venus in four Earth days. Venus' planetary body also travels in a retrograde motion; however, it takes 243 days to make one complete rotation (Kaufmann, Planets 47,53). The reason Venus has a retrograde orbit around its axis is that Venus' equator is tilted 117 degrees with respect to its orbital axis (Abell, Morrison, and Wolff A-28). The retrograde rotation of Venus is very unusual. It is one of only three planets in the solar system which has a retrograde orbit. The other two planets are Uranus and Pluto (Kuhn 236).

If a planet's rotation is retrograde, versus prograde, then it rotates on its axis in a clockwise direction rather than in a counter-clockwise direction. One interesting fact about retrograde rotation is that if a person were to view the sun rise or sun set on a planet with retrograde rotation, they would see the sun rise in the west and set in the east (Kaufmann, Planets 47, 53).

On the surface of Venus winds blow at a rate of 3.5 meters per second. Due to the difference in rotational direction and speed and the relatively slow winds on the surface of Venus, a tremendous shear in the clouds above Venus exists where the transition from high speed to low speed takes place (Kaufmann, Planets 57).

The surface of Venus is ruled by volcanos, craters and faults. One particular area of interest is the region called Ishtar Terra. It is a lava-filled basin as large as the continental United States. In this region there exists a

Mount Everest sized mountain named Maxwell Montes. On the side of this mountain is a tremendous crater called Cleopatra. It is 100 kilometers wide and 2.5 kilometers deep, and may date back to as far as 400 million years ago. Craters on Venus tend to last that long because there is little erosion from wind. There is also no erosion from water because water does not exist on Venus (NASA: Our Solar System 9).

Most of the surface of Venus is approximately 400 million years old. Though older than the 3.5 million year old face of Earth, Venus' surface is relatively young when one considers the age of Earth's moon's surface. Some Moon rocks date back to 4.2 billion years ago. To explain the relative youth of Venus' surface, scientists believe that there had to be one or more cataclysmic events which occurred to cause Venus to resurface. At NASA's Jet Propulsion Laboratory, Magellan project scientist Stephen Saunders believes that approximately 400 million years ago, a tremendous lava flood which resurfaced Venus occurred (Cook 62,63).

Roger Phillips of Southern Methodist University believes that the combination of patches of craters and smooth land on Venus' surface implies that Venus' resurfacing did not happen all at one time. Instead, Phillips believes that Venus' resurfacing was the result of several small catastrophes. He proposes that the smooth areas were the result of fairly recent events which filled in the craters. If the craters concealed beneath the smooth surfaces are considered, then

Venus' surface can be dated back to nearly one billion years ago (Cook 64).

On the surface of Venus, there are many faults and cracks. It is thought that they formed in the same way that many of the faults on Earth formed. However, the faults did not divide Venus' single land plate into several land plates, or grow to the magnitude of Earth's San Andreas Fault. These structural changes did not occur because the heat on Venus' surface was so great that it caused the rocks to weaken and crack in several places and thereby prevented these changes from taking place (NASA: Our Solar System 9).

Instead of several plates, as on the Earth, Venus is made of a single plate. Though it may have originated with more than one plate, scientists believe that the temperatures on Venus became too great for the rocky plates to stay solid. They believe that the rocks melted together to form one plate (Burnham, What Makes 41).

Venus' current atmosphere is not its original one. The blistering heat from the Sun was too strong for Venus, or any of the other rocky planets, to retain their original atmospheres. Venus' current atmosphere is about 96% carbon dioxide and 3.5% nitrogen. The remaining 0.5% consists of traces of water vapor and other gases (Hartmann and Impey 199; Arny 204).

One theory about the origin of the current atmospheres on the terrestrial planets (Mercury, Venus, Earth and Mars) is that they are the result of volcanic activity and global plate tectonics. However, some scientists discount this theory because Venus does not show any evidence of global plate tectonics (Broadhurst 43).

Another theory for the origin of the current atmospheres of the terrestrial planets is that cratering and impact from planetesimals created the atmospheres. During a period between 3.6 and 4.0 billion years ago, called the period of heavy bombardment, there were a great number of planetesimals striking the terrestrial planets. T. Matsui and Y. Abe of Japan believe that the four inner planets were bombarded by comets and water-rich asteroids during the later stages of planetary accretion. According to this theory, Venus was covered by a very thick atmosphere of steam. This atmosphere was 100 times more dense than Earth's present atmosphere. As the impacts continued, Venus grew hotter because its atmosphere contained the heat in a greenhouse effect. The surface of Venus was completely covered in molten rock. Then, over time, the number of impacts lessened and ultraviolet radiation from the Sun allowed the water in Venus' atmosphere to escape, leaving behind an atmosphere heavy with carbon dioxide (Broadhurst 43).

According to other scientists, deep in Venus' past, when the Sun was smaller and radiated less heat, oceans may have existed. But as the Sun's heat increased, Venus' surface temperature increased and its oceans began to boil away.

Through volcanic activity, carbon dioxide was ejected into the atmosphere. Since there was no water left to recycle carbon dioxide back into Venus' crust, the levels of carbon dioxide in the atmosphere rose. The excess carbon dioxide created a greenhouse out of Venus' atmosphere. Solar energy penetrated the atmosphere, but infra-red radiation was trapped inside the greenhouse (Burnham, What Makes 41).

Of all the planets in our solar system, Venus has been visited the most. Between the U.S. and Soviet space missions, Venus has been viewed by probes more than 25 times (NASA: Our Solar System 9). We have learned a great deal from these missions, but there is still a lot we do not know and hope future missions will reveal.

Chapter 4
The Earth

Orbiting the Sun at an average distance of 150 million kilometers (1.000 AU) is the only planet known to harbor any form of life. It has a diameter of 12,756 kilometers, a surface gravity of 1.0 and an average temperature of 288 degrees Kelvin (15 degrees Celsius). The surface pressure on this remarkable planet is 1.0 bar. This planet is the Earth (Broadhurst 44; Arny A-27).

About five billion years ago the Earth began to form. It accreted into a sphere larger than its present size (Engelbrektson 114). Some geologists believe that the Earth was entirely molten soon after it formed (Kaufmann, Planets 152). The cause for its molten state is likely to be due to its accumulation of mass during formation. As the Earth continued to gather mass from asteroids and meteoroids which struck its surface, it began to compress. This compression and the decay of radioactive elements caused the temperature of the forming planet to rise to such high levels as to melt rock and metal. Through differentiation, the heavy elements (iron and nickel) separated and formed the inner core of the Earth. A mantle of silicates formed outside of the core. The outer layer of the Earth, the crust, formed from lighter silicates which did not differentiate with the dense silicates composing the mantle. The light silicates of the crust cooled and solidified. From cracks and fissures venting gasses and mountains and geysers of molten rock squeezing from the mantle, the Earth's atmosphere formed (Engelbrektson 114). High in the atmosphere, where temperatures were much cooler, the water vapor condensed and formed thick clouds which prevented the Sun's rays from touching the Earth. A downpour of rain fell, lasting thousands of years. But the temperature on the surface of the Earth was still very high and this caused the rain to evaporate. Eventually surface temperatures cooled and the rain began to collect in basins on the surface of the Earth. During this time, volcanos spewed molten rock from the mantle. The lava cooled and built up the crust. This volcanic activity also provided gases for the atmosphere. Eventually the volcanos stopped and the rains ceased. The Sun broke through the clouds and Earth was bathed in the Sun's rays (Engelbrektson 114).

The Earth's solid inner core is its densest part. It is estimated to have a density of 17 grams per cubic centimeter. Scientists believe that it is made of iron and nickel. The inner core has an estimated radius of 1,220 kilometers. This value is only a little less than the radius of the Moon. Enclosing the inner core is a transitional zone approximately 500 kilometers thick. Outside the transitional zone is a 1,700 kilometer thick liquid outer core. The outer core is able to conduct electricity. The electric current is continually produced by the "dynamo action of the spinning core." It is considered to be the source of the Earth's magnetic field (Engelbrektson 114-115).

Outside the inner core lies the mantle. Almost 70% of the Earth's mass is attributed to the mantle. Its density ranges from 3.3 grams per cubic centimeter below the crust, to 5.6 grams per cubic centimeter outside of the liquid outer core (Engelbrektson 116). The mantle is made of a silicate mineral called olivine. Olivine is a rock combination of iron, magnesium and a compound of silicon and oxygen (Zeilik 155).

Between the crust and mantle lies a layer called the Mohorovicic Discontinuity (Moho). It is considered to be a transitional layer where the silicates of the mantle and the rocks of the crust mesh and then begin to separate to form the next layer of the Earth. The thickness of the Moho varies with the thickness of the crust. Below the ocean floor, it is approximately 10 kilometers thick, and below the continents, it is approximately 30 kilometers thick. There are also variances in the thickness of the Moho where the mantle's thickness varies (Engelbrektson 114).

The outer-most layer of the Earth is called the crust. It is defined as "the solid portion of the Earth above the Moho." The crust constitutes the continents and the ocean floors. The average thickness of the crust is 35 kilometers, but the actual thickness of the crust varies from location to location. Under the oceans it ranges from 5 to 12 kilometers, and the continental crust ranges from 100 to 150 kilometers (Engelbrektson 116).

Most of the crust is made of igneous rocks. Igneous rocks are solidified forms of molten lava. The ocean basins and subcontinental sections of the crust are made of a form of igneous rock called basalt. Basalt is a silicate of aluminum, magnesium and iron. Granite is an igneous form of rock that makes up most of the continental masses. It is a silicate of aluminum, sodium and potassium (Zeilik 155).

The Earth has what is known as a secondary atmosphere. In other words, Earth's present atmosphere is not its original atmosphere. Scientists believe that the Earth originally had an atmosphere composed of lightweight gases like hydrogen, methane, ammonia and water vapor. Through solar ultraviolet radiation, the hydrogen in these gases was released. The Earth's gravitational field was not strong enough to retain the extremely lightweight hydrogen gas and thus, the very tenuous hydrogen atmosphere escaped (Arny 126-127).

The Earth's secondary atmosphere is made of heavier gases. The break-down of the Earth's atmosphere is as follows.

Nitrogen	78.08%
Oxygen	20.95%
Argon	0.93%
Water	0.1% - 3.0%
Carbon dioxide	0.03%

Trace gases (less than 100 parts per million)
Neon, helium, ozone, krypton, hydrogen, methane, carbon monoxide and many natural and man made pollutants (Arny 126).

There are two prominent theories about how the Earth's present atmosphere (excluding oxygen) was created. One theory holds that it was created by volcanic eruptions during the early stages of the Earth's formation. As rocks which had trapped gases in the Earth's crust were heated, the trapped gases were freed into the atmosphere (Arny 126).

Geologists have studied the gases ejected in volcanic eruptions today. Their data shows that many of the gases in the Earth's present atmosphere are the very same gases ejected in volcanic eruptions. If the volcanic activity in the past was as frequent as it is now and the volumes of gas expelled in volcanic eruptions is equitable to that expelled now, then this theory is very plausible (Arny 126).

Other astronomers, however, have suggested that the Earth's current atmosphere was created through a series of impacts from comets on the newly formed Earth. Comets are made of a mixture of ice and frozen gases. If a large number of comets hit the early Earth, then they would have provided enough water and gases to make up the Earth's oceans and present atmosphere (Arny 127).

The oxygen in the Earth's atmosphere can not be accounted for in either of these two theories. Instead, scientists believe that the oxygen in the Earth's atmosphere was created in two ways. One way is through a process called photosynthesis. In this process, plants take in water and convert it to oxygen (Arny 127-128).

Through chemical analysis of rocks on the Earth, scientists have discovered that the amount of oxygen in the

Earth's atmosphere was once a lot less than it is today. They believe that the oxygen in the Earth's atmosphere has been increasing with the increase of plant life over a period of three billion years (Arny 126-127).

The second process which accounts for the oxygen in the Earth's atmosphere involves solar ultraviolet radiation. According to this theory, the ultraviolet radiation from the Sun caused the hydrogen and oxygen molecules in water to split. Once divided, the lightweight hydrogen molecules and heavier oxygen molecules floated into the atmosphere. Because the Earth's gravity was too weak to hold on to the light hydrogen molecules, they escaped the Earth's atmosphere. The end result was that only oxygen molecules were left (Arny 127).

Astronomers learned many things about the Earth from space missions and satellites orbiting the Earth. They have discovered that external astronomical events can influence the Earth in different ways. Some things attributed to external astronomical influence are the ice ages, the thinning ozone layer, mass extinctions of species, and numerous other events (Hartmann and Impey 145-146). Astronomers continue to learn new things about the Earth as they interpret data from flybys and satellites. It is very exciting to imagine what they will discover about our planet in the future.

Chapter 5
Mars

Mars is the fourth and final terrestrial planet. It lies almost 228 million kilometers (1.5237 AU) from the Sun. Mars has a period of revolution of 686.98 Earth days and a diameter of 6,790 kilometers at its equator (NASA: Our Solar System 13; Arny A-27).

Mars is very similar to its terrestrial siblings. As with the other terrestrial planets, the crust, mantle and core of Mars were created through a process of differentiation. The denser elements in the early Martian planet sunk to the center of its body, forming its small core. Mars rotates as fast as the Earth, and astronomers have been able to detect a very weak magnetic field from Mars. From this information, they have deduced that Mars has a small, liquid, iron-nickel core (Arny 217-218).

Planetary geologists divide the history of Mars into three separate periods. The Noachian period is the earliest. It took place during the time of heavy bombardment and ceased approximately 3.5 billion years ago. In this time period, it is thought that the Martian crust formed and some of the large features on Mars developed. The next time period is the Hesperian. It is estimated to have lasted from about 3.5 billion years ago till 2.7 billion years ago. Many astronomers believe that during the Hesperian period, the large flood channels on the Martian surface formed and widespread outpourings of lava took place. The third period is the Amazonian period. It began about 2.7 billion years ago. In this era, volcanic activity in the Tharsis region may have occurred. The erosion of many of the outflow channels formed in the Hesperian period also took place during the Amazonian period. The Amazonian period is also responsible for the establishment of the present appearance of Mars (Kargel and Strom 42-43).

Planetary scientists have discovered that Mars underwent two major periods of glacial activity. They are called the Big Ice Age and the Little Ice Age. The first of the two is the Big Ice Age. It is uncertain exactly when the Big Ice Age took place, but planetary scientists have estimated that it must have occurred between two billion and 300 million years ago. The age of the Little Ice Age is also uncertain. Planetary scientists have estimated that it took place between 300 million years ago and the present. The Little Ice Age is believed to be the cause of the present-day Martian climate (Kargel and Strom 42-44).

During the Big Ice Age, huge sheets of ice moved across the Martian surface. The ice sheets indicate that the early climate on Mars was very different from the present Martian climate. The advancing ice sheets required a steady snowfall during the winter. The melting of these sheets required either a warm atmosphere or geothermal heat from the inside of Mars (Kargel and Strom 43).

Through research, scientists have concluded that the ice sheets on Mars came from substantial water deposits and required a way to cycle water through the atmosphere. There is evidence to show that water deposits of oceanic proportions existed in the northern regions of Mars during a period spanning the late Hesperian and middle Amazonian periods. This coincides with the era of the Big Ice Age. Scientists have also been able to date the creation of the large channels to this time period (Kargel and Strom 45). These channels are thought to have formed from outflows of liquid water from water-bearing rock formations or aquifers beneath the surface of Mars (McKay 29). The water in the northern region would have evaporated into the atmosphere and returned to the land as snow (Kargel and Strom 44-45). The age of the channels suggests to planetary scientists that liquid water may still exist under the surface of Mars (McKay 29).

Unlike Earth, with its multiple tectonic plates, "Mars is a one-plate planet" (Seeds 507). Some prominent features on the Martian surface are Valles Marineris, the polar ice caps, the Tharsis bulge and Olympus Mons. Valles Marineris is a huge canyon running along part of the equator of Mars. It is about 5,000 kilometers long (Zeilik 212). If laid across the United States, Valles Marineris would span the distance from California to Florida (Arny 212). The depths of Valles Marineris drop to six kilometers below the surface of Mars, and its breadth is an average 100 kilometers across (Engelbrektson 154). Some planetary geologists believe that this huge gash on the Martian surface is the result of swelling in the Tharsis region. As the Tharsis region swelled, the crust stretched and cracked (Arny 211).

A second theory about the formation of Valles Marineris is that it points toward activity in the plate tectonics of Mars. The planetary geologists who adhere to this theory believe that Valles Marineris is a region of the Martian crust which began to split as the crust attempted to separate itself into different tectonic plates. But the motion of the crustal plates ceased as Mars aged and cooled (Arny 213-214).

On the equator of Mars is a large, irregular volcanic dome called the Tharsis bulge. It rises to heights of 10 kilometers in elevation and extends from the north to the south over thousands of kilometers. In the center of the Tharsis bulge is a ridge covered by a shield of volcanoes. The volcanoes on the Tharsis ridge are monstrous compared to the largest of volcanoes on Earth. In a region on the Tharsis ridge, from the southwest to the northeast, there are three large volcanoes. Each of them have base diameters of approximately 400 kilometers. In the northwest lies the largest volcano in the known solar system. It is called Olympus Mons. It rises upward to a height of over 25 kilometers and the diameter of its base covers over 500 kilometers of the Martian terrain. If compared to the eastern coast of the United States, its base would be the same diameter as the distance from Boston, Massachusetts, to

Washington, D.C. (Engelbrektson 152-153) and its height would be over three times as high as the tallest of Earth's peaks (Arny 213).

As with those of the Earth and Venus, the Martian atmosphere is a secondary atmosphere. Mars' original atmosphere is thought to have been rich in carbon dioxide. It is believed that the carbon dioxide was the result of outgassing from the interior of Mars. As the thick carbon dioxide atmosphere trapped infrared radiation from the Sun, it produced a greenhouse on Mars. The warmth of the Martian atmosphere allowed water to flow freely. Then, as the water and carbon dioxide mixed, a weak carbonic acid was formed. Reacting with rocks on the Martian surface, the carbon was transformed into carbonates. These carbonates then precipitated onto ocean and lake basins on the surface of Mars. As this process continued, the carbon dioxide was not renewed (McKay 30-31).

Mars' current atmosphere is very thin. It is still mostly carbon dioxide. Today, Mars' atmosphere has the following chemical breakdown (Hartmann and Impey 215).

Carbon dioxide	95.00%
Nitrogen	2.70%
Argon	1.60%
Carbon monoxide	0.60%
Oxygen	0.15%
Water vapor	0.03%
Krypton	Trace
Xenon	Trace
Ozone	0.000003%

(Hartmann and Impey 218)

Orbiting Mars are two small moons called Phobos and Deimos. They are both about 10 kilometers across. Because of their small size, their gravity was not strong enough to shape them into spheres. As a result, they have irregular shapes. Most astronomers believe that Phobos and Deimos are captured asteroids (Arny 218).

Their surfaces are cratered, and Phobos' surface also has cracks. These characteristics suggest that some time in the past, Phobos and Deimos were bombarded by objects. The cracks on Phobos allude to a collision with an object large enough to almost split it apart (Arny 218).

We know a great deal more about Mars than we did in the past. Many old theories have been replaced with more substantial theories or conclusive proof. But we still have a great deal to learn.

Chapter 6
Jupiter & Saturn

The Jovian planets are the ones "whose physical properties resemble those of their prototype--Jupiter" (Zeilik 221). Jupiter is the largest planet in our solar system. While the Sun accounts for 99.80% of the mass in the solar system, 0.10% is accounted for by Jupiter. When combined, all of the other planets in the solar system account for only 0.04% of the solar system's matter (Abell, Morrison, and Wolff 170).

Jupiter lies 5.2 AU from the Sun and its diameter is approximately 142,800 kilometers. It has a mass of 318 Earth masses and its density is 1.3 grams per cubic centimeter. One year on Jupiter would last 11.9 Earth years and one day on Jupiter would last 9.9 hours (Abell, Morrison, and Wolff 172).

Saturn is the second largest Jovian planet and next door neighbor to Jupiter. It lies 9.5 AU from the Sun and its diameter is about 120,540 kilometers. Saturn's mass is calculated to be 95 Earth masses and its density is 0.7 grams per cubic centimeter. One Saturnian year would last 29.5 Earth years and one Saturnian day would last 10.7 hours (Abell, Morrison, and Wolff 172).

The Jovian planets began forming by accreting planetesimals, as did the terrestrial planets. But the space around the Jovian planets was farther away from the Sun and, therefore, much colder than the space around the terrestrial planets. The lower temperatures meant that icy matter existed in the space around the Jovian planets. With the greater abundance of material to collect into the forming planets, the Jovian planets grew much larger than the Earth. When their masses reached approximately 15 times the mass of the Earth, their gravity became so strong that it started pulling gases from the surrounding solar nebula (Hartmann and Impey 237-238, 269).

The Jovian planets are considered to be two-phase planets. They are composed of a terrestrial-planet-like core and a thick outer shell of hydrogen and helium gas. The gaseous shell is considered the Jovian planets' atmospheres. The gases in their atmospheres were never accreted into the solid part of the planet because the solid core of each giant planet was not massive enough to accommodate the tremendous amounts of hydrogen and helium collected in their atmospheres (Hartmann and Impey 238).

Jupiter and Saturn have very similar atmospheres. They are each composed of hydrogen, helium and trace amounts of ammonia, methane and water vapor. Both atmospheres are divided into layers. Jupiter's atmosphere begins where the atmospheric pressure is weak enough to allow the gaseous state of hydrogen to exist. Jupiter's atmosphere contains helium, hydrogen, small doses of ammonia, methane, hydrogen sulphide and water vapor as well as traces of deuterium acetylene, ethane and phosphine. When broken down, Jupiter's atmosphere is made of several layers. The innermost layer is called the troposphere. From closest to Jupiter's surface outward, the troposphere is layered as follows (Engelbrektson 164-165).

(1) A thin base cloud of water ice.
(2) A level of clear gas.
(3) A layer of dense ammonia cloud and possibly ammonium hydrogen sulphide crystals.
(4) A layer of ammonia haze.
(5) A second layer of clear gas (Engelbrektson 165).

Between the first and second layer of Jupiter's atmosphere is a transitional zone called the tropopause. The second layer is called the stratosphere and it contains two levels:

(1) A layer of methane and dust;
(2) A layer of clear gas (Engelbrektson 165).

Saturn's atmosphere is also separated into a troposphere and stratosphere. Scientists do not presently know what composes the inner layers of Saturn's troposphere. The only layers of Saturn's troposphere which have been distinguished are the outer layers. They are:

(1) A clear layer consisting of hydrogen and helium;
(2) A layer of water ice clouds;
(3) A layer of ammonium hydrogen sulfide clouds;
(4) Another clear layer of hydrogen and helium;
(5) A layer of white ammonia crystals (Engelbrektson 176-177).

Saturn's tropopause is also a transition zone between the troposphere and stratosphere. The make up of Saturn's stratosphere resembles Jupiter's stratosphere to a great degree (Engelbrektson 175-176).

Though the composition of the atmospheres of these two

Jovian planets is very similar, the thickness of their atmospheres is far from similar. Jupiter's cloud layer has been compressed by its tremendous gravity until the cloud layer is only 75 kilometers thick. Saturn, having a much weaker gravitational force, did not compress its cloud cover as much as Jupiter. Instead, Saturn's cloud layers are spread over 300 kilometers (Kaufmann, Universe 291).

The internal structures of Jupiter and Saturn are very much alike. They each have a solid rocky core surrounded by a mantle of liquid metallic hydrogen and an outer layer of molecular hydrogen. The differences in their inner structures lies in the proportioning of the different layers of their structures (Kaufmann, Universe 288).

By studying the rotation of Jupiter and Saturn, scientists have determined quite a bit about their internal structures. In 1690, an Italian astronomer named Giovanni Domenico Cassini discovered that Jupiter rotates differentially. This meant that Jupiter's polar regions were rotating at a slower rate than its equatorial regions. Much later in history, scientists used measurements of the radio emissions from Jupiter to determine that Jupiter's atmosphere rotated at a slightly different rate from the Jovian interior. Other studies of Jupiter's rotation showed scientists that Jupiter's rapid rotation rate caused Jupiter's spherical shape to flatten slightly at the pole. Thus, Jupiter has a slight oblateness of 0.065 (Kaufmann, Universe 248).

Jupiter's slightly oblate shape gave scientists very important information about its interior. Through very detailed calculations William Hubbard, an American scientist from the University of Arizona, and two Soviet scientists, V. Zharkov and V. Trubitsyn, came to the conclusion that 4% of Jupiter's mass was concentrated in a solid, dense, rocky core. This core is almost 13 times as massive as the Earth. However, the remainder of the matter composing Jupiter pressed down on Jupiter's inner core with a pressure equivalent to the mass of 305 Earths. This caused Jupiter's core to be compressed into a sphere slightly less than twice the size of the Earth, with a density of 20 grams per cubic centimeter. The tremendous pressures exerted on Jupiter's core caused the temperature in its core to reach an estimated 25,000 degrees Kelvin (~25,000 degrees Celsius) (Kaufmann, Universe 248-250). Compare this to Jupiter's cloud-top temperature of 124 Kelvins (-149 degrees Celsius) (Engelbrektson 164).

Some scientists believe that the core of Jupiter consists of two parts. The innermost core is thought to be made of iron-silicate. It is estimated to have a radius of 6,700 kilometers. Outside of the inner core, may lie a 6,700 kilometer thick layer of methane and ammonia liquid/ice (Engelbrektson 164).

The next 15,600 kilometers outside the core was thought to be liquid metallic hydrogen. Twelve-thousand-four-hundred-and-ninety-two kilometers from the liquid metallic hydrogen layer exists a layer of liquid molecular hydrogen. The outermost layer is Jupiter's atmosphere (Engelbrektson 164).

Through analyzing the rotation rate, density and oblateness of Saturn, scientists have been able to come up with theoretical models for its composition. Studies of Saturn show that it has an oblateness of 0.11. This illustrates that Saturn has a larger degree of oblateness than Jupiter. But Saturn also has a slower rotation rate than its neighbor and a density which is much less than Jupiter's. Compare Saturn's overall density of 0.7 grams per cubic centimeter to Jupiter's overall density of 1.3 grams per cubic centimeter. All of this information has led scientists to believe that Saturn has a much larger and more massive core than Jupiter (Kaufmann, Universe 288).

It has been determined that Saturn's core makes up an estimated 26% of its mass. This is much greater in comparison to Jupiter's core, which makes up only 4% of its mass (Kaufmann, Universe 288).

The make-up of Saturn is much like that of Jupiter. Saturn's inner core is thought to consist of metals and silicates. Its outer core is probably made of water, methane and ammonia liquid/ice. Combined, the inner and outer core of Saturn are estimated to have a radius of about 12,656 kilometers (Engelbrektson 175).

The next 13,862 kilometers of Saturn consist of helium and liquid metallic hydrogen. The formation of helium droplets makes up the next 3,616 kilometers. The layer on top of that is believed to be approximately 93% liquid molecular hydrogen and 7% helium. This layer is about 30,134 kilometers thick. The outermost layer is Saturn's gaseous atmosphere of hydrogen and helium (Engelbrektson 174-175).

Jupiter's atmosphere is divided into light and dark regions. The light regions are called zones. They represent areas of temperatures lower than the darker regions of Jupiter's atmosphere. These dark regions are called belts (Zeilik 222).

Jupiter's atmosphere is dominated by wind streams and whirling vortices. The tremendous speed at which Jupiter rotates causes permanent high pressure zones and low pressure belts. Jet streams between the belts and zones cause horrendous disturbances in Jupiter's atmosphere (Zeilik 222-223).

In 1630, Robert Hooke first observed the most well-known atmospheric disturbance on Jupiter. In its southern hemisphere there is a rising region of high pressure rotating once every seven days in a counterclockwise direction. This enormous disturbance is called the Great Red Spot (Zeilik 223).

Saturn's atmosphere is also dominated by belts and zones. It is much more difficult to see details in Saturn's atmosphere due to the fact that Saturn is much colder than Jupiter. Because of the colder temperatures around Saturn, the ammonia gas in Saturn's atmosphere freezes into cloud particles. These cloud particles obscure our view of Saturn's deeper layers and markings (Arny 240).

One feature of Saturn we are able to view in detail are Saturn's rings. In the early part of this century, astronomers thought that Saturn's rings were made of matter left over from the formation of Saturn. Recently astronomers have realized that the matter in Saturn's rings is actually very young when compared to the age of the solar system (Arny 243). It is thought that the matter comes from the fragmentation of a moderate-sized icy moon blown apart by a meteorite impact. Some recent calculations suggest that within a time period less than the age of the solar system, the matter in Saturn's ring system would spiral inward toward Saturn (Hartmann and Impey 251).

Regardless of where the matter in Saturn's rings came from, astronomers have been able to determine what makes up Saturn's rings. In 1970, American astronomers discovered that Saturn's rings were made of chunks of ice. The size of the ice chunks is variable. Some pieces are as small as Ping-Pong balls, while others are large enough to be houses (Hartmann and Impey 249).

Saturn's ring system measures approximately 274,000 kilometers from edge to edge. Though it is a vast system, Saturn's rings are not very thick; they probably measure less than 100 meters in thickness (Hartmann and Impey 249).

The rings are divided into a system of darker and lighter rings. Within each system exist thousands of rings. There is a single wide gap separating the lighter rings from the darker rings. This gap is called Cassini's division. Inside of Cassini's division are only a few tiny ring particles (Hartmann and Impey 248).

Jupiter also has a ring system. It was discovered in 1979 by astronomers gathering data from the flight of Voyager I. Jupiter's ring system is nowhere near as extensive as Saturn's (Arny 235). In fact, it resembles Cassini's division more than the actual rings of Saturn (Hartman and Impey 248). Jupiter's rings are very thin; they measure less than 30 kilometers in thickness. The particles in Jupiter's ring are very, very tiny. They are estimated to be about 10 micrometers (10×10^{-6} meters) in size. It is not yet known what the particles in Jupiter's ring system are made of (Zeilik 229-230). There are some scientists who believe that the particles making up Jupiter's ring system are dust particles resulting from meteorite impacts on Jupiter's innermost moons. They think that debris "sandblasted" off of the moons may have been captured in Jupiter's tremendous gravitational field (Arny 235).

The outermost ring lies at an approximate distance of 128,500 kilometers from Jupiter's center. It is about 800 kilometers wide and is the brightest of Jupiter's rings. Inside of this ring lies a second ring which is about 6,000 kilometers wide. Within that ring lies a sheet of particles which is very faint. The sheet is about 119,000 kilometers wide (Zeilik 230). It is made of particles which are gradually falling into Jupiter's atmosphere (Hartmann and Impey 248).

Orbiting Jupiter are at least 16 moons. Some of them are considered the largest planetary satellites in the solar system. Jupiter's moons are divided into four categories according to their distances from Jupiter. In the first category are the Galilean satellites. They are Io, Europa, Ganymede and Callisto. The satellites in the second category are Amalthea, Adrastea, Thebe and Metis. In the third category are the moons Leda, Himalia, Lysithea and Elara. The group farthest from Jupiter includes Ananke, Carme, Pasiphae and Sinope. The satellites in the final category all orbit Jupiter in a retrograde fashion (Engelbrektson 168-169).

An interesting pattern involving the Galilean moons involves their orbits. Each Galilean moon's density is inversely proportional to its distance from Jupiter. In other words, the farther from Jupiter the moon's orbit is, the less dense the moon (Zeilik 226).

The inner moons of Jupiter are made mostly of rocky materials. Farther out, the moons are made more of low-density icy materials than rock. Jupiter's farthest orbiting moons are considered to be captured asteroids (Zeilik 226-229).

Perhaps the most interesting of Jupiter's satellites is the moon Io. It is considered to be the most volcanically active body within the known solar system (Zeilik 226). Its extensive volcanic activity is credited to Jupiter's gravitational pull. Because of Jupiter's gravity, Io experiences tidal flexes. The tidal flexes cause Io's interior to heat to temperatures sufficiently high to account for its volcanic activity (Engelbrektson 169).

Io is also one of only three satellites in the solar system known to have an atmosphere. Its atmosphere is very thin and is made, for the most part, of sulfur dioxide (Zeilik 226).

Saturn has at least 18 known satellites. Astronomers have separated them into groups according to characteristics they share. The first group are the Inner Satellites. They orbit Saturn close to the outer edge of its rings (Hartmann and Impey 252, 263). Pan, Atlas, Prometheus, Pandora, Epimetheus and Janus form the group of Inner Satellites (Arny A-4). Each of them is very small and potato-shaped. "The largest one is a respectable 220 x 160 kilometers (about the size of New Hampshire and Vermont)." They are believed to consist of almost completely pure ice (Hartmann and Impey 263).

The second group are the Midsized Satellites. They are Mimas, Enceladus, Tethys, Dione and Rhea. Their diameters range from 300 to 1,500 kilometers. Each of the moons is bright-colored and cratered. Because their surface densities are very low and their surfaces are very bright, astronomers have concluded that they are made mostly of ice. Astronomers have also found evidence to support the theory that the Midsized Satellites have some form of internal heating. Their evidence is the large canyons on the satellites' surfaces. The canyons may be the result of expansion in the crust due to internal heat which fractured the crust so as to be able to escape (Hartmann and Impey 263).

During one Voyager mission, three small, unusual satellites were discovered: Calypso, Telesto and Helene (Hartmann and Impey 264). Calypso and Telesto share Tethys' orbit, and Helene shares Dione's orbit (Arny A-4). These small satellites have very irregular shapes, and the average diameter of each of them is only 30 kilometers. The 60 degree lag/lead of the small satellites provides the stability which makes the likelihood of collision practically nonexistent (Hartmann and Impey 264).

The final group of satellites are the Major Satellites. They are Titan, Hyperion, Iapetus and Phoebe (Arny A-4). One of the most interesting satellites in the entire solar system is the first of the Major Satellites: Titan. It is the largest of Saturn's satellites and one of the largest satellites in the entire solar system. It has a diameter of 5150 kilometers and is second in size only to Jupiter's satellite Ganymede. Titan is terrestrial in nature. It is also one of the three moons that have atmospheres (Engelbrektson 177-178). In 1944, astronomers discovered that Titan's atmosphere contained methane. Later observations showed that it also contained excessive amounts of smog. After the Voyager missions, astronomers discovered that the smog and methane make-up only 10% of Titan's atmosphere. The most abundant component of Titan's atmosphere is nitrogen. Titan's atmosphere also includes small amounts of ethane, acetylene, ethylene and hydrogen cyanide which are all organic molecules. The tremendous amount of nitrogen and organic molecules in Titan's atmosphere gives astronomers hints about the origins of the Earth and life on the Earth (Hartmann and Impey 264-265).

The other Major Satellites also have unusual characteristics. For instance, Hyperion has a biscuit-shaped body and an irregular rotation rate produced by its wobbling motion. Iapetus is "two-faced." One side of Iapetus is black and the other side is white. The cause of the black coloring of half of Iapetus is a layer of black dust. It is believed that the dust comes from Phoebe, the final Major Satellite. Astronomers think that meteorite impacts on the surface of Phoebe cause black dust particles to blow off of Phoebe. As gravity causes the dust particles to spiral toward the surface of Saturn, half of Iapetus gets hit by the dust particles and turns black. Phoebe's most unusual characteristics are its retrograde motion about Saturn and the fact that its tremendous distance from Saturn does not fit the pattern set by the Saturn's other satellites (Hartmann and Impey 265, 268).

In December of 1995, the American Galileo space probe is expected to arrive at Jupiter. This probe will give accurate mappings of several of Jupiter's satellites and will parachute the first probe into Jupiter's atmosphere. After the turn of the century, American and European scientists will launch the Cassini space probe. This probe will map Saturn's moons and parachute a probe into Titan's atmosphere (Hartmann and Impey 268). These, and future projects, provide hope for astronomers who want to unravel the mysteries of Jupiter, Saturn and their unique satellites.

Chapter 7
Uranus & Neptune

The March 13, 1781, entry in William Herschel's journal reads, "In examining the small stars in the neighbourhood of H Geminorum, I perceived one that appeared visibly larger than the rest." That star was Uranus. It was not long until he was hailed as an "astronomer-hero" by the English public for his discovery of the seventh planet in our solar system (Seeds 546-547).

In 1843 two astronomers began work on a problem. Calculations made to determine the orbit of Uranus did not fit Uranus' actual orbit. John Couch Adams in England and Urbain Jean Leverrier in France worked independently on this problem. Eventually, they discovered that there had to be an eighth planet, farther from the Sun than Uranus, to explain the discrepancies in Uranus' orbit. In October of 1845, Couch sent his calculations and discovery to Sir George Airy, the Astronomer Royal in Great Britain. Unfortunately his discovery was not taken seriously. At the same time, across the Channel, Leverrier sent his prediction for the orbit of the eighth planet to Johann Galle at the Berlin Observatory. On the afternoon of September 23, 1846, the astronomers at the Berlin Observatory used Leverrier's calculations to find the eighth planet. After only 30 minutes of searching the sky, they found Neptune. For centuries the English and French argued over who had made the first discovery of Neptune.

Eventually, credit for the discovery was given to both Couch and Leverrier (Seeds 560).

One irony in the discovery of Neptune lies in the fact that, 234 years earlier, Galileo had seen Neptune. On December 27, 1612, and January 28, 1613, Galileo made note of Neptune in his journal. Unfortunately, he was so involved in studying Jupiter that he did not realize what he had seen and plotted Neptune as a star (Seeds 560).

Uranus and Neptune are the last two Jovian planets and are often considered twins. They have several common characteristics, such as color, size, inner structure and atmospherical composition. Uranus lies approximately 19 AU from the Sun while Neptune lies 30 AU from the Sun. Uranus' equatorial diameter is estimated at 51,118 kilometers and Neptune's at 49,500 kilometers. These figures are equivalent to 4.01 and 3.93 times the diameter of Earth, respectively (Seeds 548,562).

When viewed through a telescope, Uranus and Neptune appear blue. This is very unusual coloring when compared to the other planets. Their blue appearance owes to the composition of their atmospheres. Uranus' atmosphere consists of 65% hydrogen and 23% helium. The remaining 12% is composed of various gases, including traces of methane. Neptune's atmosphere is composed of 63% hydrogen and 25% helium. Like that of Uranus, the remaining 12% of Neptune's atmosphere consists of various gases, one of which is methane. It is the methane in their atmospheres which is responsible for their blue coloring. As the white light radiated by the Sun hits Uranus and Neptune, the red and orange light is absorbed by the methane in their atmospheres. Thus, only blue light is reflected back outward and that is what we see through our telescopes (Zeilik 235; Seeds 550).

Through information inferred from the gravitational fields and rotation periods of Uranus and Neptune, hypothetical models of their interior structures have been made. The models of their interior structures are as much alike as the composition of their atmospheres and their sizes. Current theory states that each planet is composed of two layers: a core and a mantle. The small inner core of each planet is made of iron and silicates (Engelbrektson 186, 192). The outer layer, the mantle, is made of very compressed liquid water and methane. Some rocky minerals are also included in the mantle (Hartmann and Impey 275).

Though they share many similarities, Uranus and Neptune also have several differences. For instance, Neptune is slightly smaller and denser. Neptune's mass and average density are 17.23 Earth masses and 1.66 grams per cubic centimeter, respectively. Uranus, on the other hand, has a mass of 14.54 Earth masses and an average density of 1.19 grams per cubic centimeter (Seeds 548, 562).

Another characteristic which differentiates Uranus from Neptune is the activity in and appearance of their atmospheres. Uranus is covered by a deep layer of hazy gas, which almost obscures its deep cloud deck. For this reason it is very difficult to see any dark belts in its atmosphere (Hartmann and Impey 273).

The characteristics of Neptune's atmosphere are not so difficult to see. Like Jupiter and Saturn, Neptune has belts of darkness due to atmospherical pressure changes. Neptune also includes a system of bright clouds and a "bright hood" which caps its south polar region. Arguably the most remarkable characteristic of Neptune's atmosphere is the Great Dark Spot which lies at 20 degrees south latitude. It is 2,500 kilometers wide and 6,000 kilometers long. Just like Jupiter's Great Red Spot, the Great Dark Spot on Neptune is not stationary. It moves westward at a speed of approximately 1,000 kilometers per hour retrograde with respect to Neptune's rotation. As the Great Dark Spot moves along its course, bright clouds tend to form and stretch out 50 to 200 kilometers across. During one complete revolution, these clouds dissipate and are replaced by new ones generated lower in Neptune's atmosphere (Engelbrektson 190-192).

Current theory indicates that the Great Dark Spot is a huge high pressure dome as large as the Earth which creates a hole in the methane cloud layer in Neptune's atmosphere. This hole exposes a deeper and darker blue-green region in Neptune's gaseous envelope (Engelbrektson 191, 192).

Some other characteristics of Neptune's atmosphere are

Scooter and Dark Spot Two. Scooter is the largest of Neptune's white clouds which are not associated with one of the dark spots. It moves around the planet in about 16 hours (the same rotation rate as Neptune). Many astronomers believe Scooter covers a hot spot deep in the interior of Neptune. Dark Spot Two is a second, smaller dark spot lying about 51 degrees south latitude (Engelbrektson 192).

One differing characteristic between Uranus and Neptune, which does not pertain to their atmospheres, involves Uranus' unusual rotation. Uranus rotates about its axis in a retrograde motion. This retrograde motion is due to the unusual tilt of Uranus' poles. Instead of having its North and South poles oriented like those of the other planets, Uranus' equator is tilted 98 degrees with respect to its orbital plane. This means that it rotates on its side. Since one Uranian year lasts approximately 84 Earth years, each pole faces the Sun every 42 years. Through calculations, astronomers have been able to determine the following time table for Uranus' orientation (Engelbrektson 184).

January 24, 1986	South pole faces Sun
January 24, 2007	Eastern Uranus faces Sun
January 26, 2028	North pole faces Sun
January 27, 2049	Western Uranus faces Sun

(Engelbrektson 184)

One theory of what created Uranus' unique tilt is that it may have been hit by a planetesimal in its distant past. Some astronomers believe that the impact not only tilted Uranus but also created its family of moons (Arny 249).

Name	Distance (km)
1986U2R	38,000
6	41,840
5	42,230
4	42,580
Alpha	44,720
Beta	45,670
Eta	47,190
Gamma	47,630
Delta	48,290
Lambda	50,020
Epsilon	51,140

(Engelbrektson 189)

In the 1980's, astronomers discovered two partial rings around Neptune. These partial rings are called "ring-arcs." Images received from Voyager II showed that Neptune's ring-arcs are actually denser portions of complete rings. Voyager II also showed astronomers on Earth two more rings. The following table gives the approximate radius and width of each of Neptune's rings.

Name	Radius (km)	Width (km)
1989N1R	63,000	17
1989N2R	53,200	17
1989N3R	42,000	1,700
1989N4R	59,000	6,000

(Engelbrektson 193)

Ring 1989N1R has three ring-arcs, which are possibly unresolved fragments that are between 10 and 15 kilometers in size. Ring 1989N3R is broad and dusty rather than narrow like Neptune's outer two rings. About 2,000 kilometers inside of ring 1989N4R is a narrow, bright ring-arc called 1989N5R (Engelbrektson 193).

Uranus is orbited by at least 15 moons. The five major moons are Oberon, Titania, Umbriel, Ariel and Miranda. They were all discovered through ground-based observations. The

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Uranus is orbited by at least 15 moons. The five major moons are Oberon, Titania, Umbriel, Ariel and Miranda. They were all discovered through ground-based observations. The remaining 10 moons were discovered when Voyager II made its flyby of Uranus in 1986. The five major moons of Uranus are made of rocky material and ice. The rock and ice differentiated during accretion into a rocky core and an icy mantle and crust. The minor satellites are made of dark grains and ice (Engelbrektson 187-188).

Neptune has at least six moons in orbit around it. Two of these moons, Triton and Nereid, were discovered through ground-based methods. The remaining four moons were discovered as a result of the Voyager II mission. Triton and Nereid are unique satellites. Nereid has the most elliptical orbit of any satellite in the solar system. It ranges from 1.39 million to 9.63 million kilometers from Neptune's center. One unique characteristic of Triton is that it travels in retrograde motion from east to west while its orbit precesses in the opposite direction (Engelbrektson 193-194).

Since Voyager II, no other flybys of Uranus or Neptune have been made. Though Voyager II gave astronomers a wealth of information about Uranus and Neptune, there are still many unanswered questions. Future missions to visit these planets are being planned. No one knows what these missions will tell us, but the possibilities are numerous.

Chapter 8
Pluto

When first discovered in 1950 by Clyde Tombaugh, Pluto was hailed as the mysterious Planet X which was believed to be the cause of the disruptions in Neptune's orbit. Later, astronomers found that Pluto was not massive enough to perturb Neptune's orbit. For years they searched for another Planet X. Then, during the summer of 1993, Myles Standish of NASA's Jet Propulsion Laboratory, published a paper which ended the search for the second Planet X. Standish reworked earlier calculations using the very accurate mass values for Jupiter, Saturn, Uranus and Neptune. These new, accurate masses were obtained from the flights of Voyager spacecrafts. His calculations showed that the perturbations in Neptune's orbit were perfectly accounted for by Pluto (Burnham, At the Edge 42,44).

Many planetary astronomers compare Pluto to Neptune's satellite Triton because of their many similarities. For instance, Pluto's diameter is about 2,300 kilometers, while Triton's diameter is about 2,700 kilometers. Their densities are also very close (2.03 grams per cubic centimeter for Pluto and 2.07 grams per cubic centimeter for Triton). Further similarities are that they both have atmospheres containing nitrogen and carbon monoxide, and their surfaces are covered in methane ice (Croswell 37-38).

The origin of Pluto is very mysterious; it is unlike any other planet in our solar system. It does not fit into the mold of the hot terrestrial planets or the large Jovian planets. Some astronomers would go so far as to say that Pluto is not even a planet. There are five reasons they make this claim.

(1) Pluto is much smaller than any other planet in our solar system. It is only 47% the size of Mercury, the second smallest planet in our solar system.

(2) Pluto's small size does not fit into the pattern set by the Jovian planets.

(3) Pluto's orbit overlaps Neptune's orbit. It is the only planet in our solar system with an orbit that overlaps another planet's orbit. Its highly irregular elliptical orbit also does not follow the spacing patterns of the other planets. Its orbit ranges from 29.7 AU to 49.3 AU from the Sun. The other eight planets have orbits which are approximately twice the size of their inner neighbor. Pluto's orbit is in no way close to twice Neptune's orbit.

(4) There have been several discoveries of interplanetary bodies, similar to Pluto, orbiting in the general region from Neptune out beyond Pluto. Some astronomers believe that a whole population of comet nuclei exists beyond Neptune. Pluto may just happen to be the largest of these interplanetary bodies.

(5) The diameter of Charon, Pluto's moon, is 57% the diameter of Pluto. No other planet in the solar system has a moon whose diameter is so close to that of the planet it orbits (Hartmann and Impey 284).

With the evidence provided above, several astronomers have concluded that Pluto is not a planet at all. Instead, they believe that Pluto and Charon are a giant double asteroid (Hartmann and Impey 284).

According to planetary scientist Alan Stern, "Pluto behaves like a comet on a planetary scale." As Pluto nears perihelion (at which point it is 4.424 billion kilometers from the Sun), its atmosphere boils off. Then, as Pluto nears aphelion (at which point it is 7.376 billion kilometers from the Sun), its atmosphere freezes out. Perihelion and aphelion are the points in a planet's orbit when the planet is closest to and farthest from the Sun, respectively. The next time Pluto's atmosphere will reappear in totality is when it reaches perihelion the year 2237 (Burnham, At the Edge 45; Engelbrektson 194).

The discovery of Pluto's moon Charon in 1978 by James Christy of the US Naval Observatory raised many questions about the formation of Charon. Some astronomers theorized that Charon was created when proto-Pluto split into two pieces as it rotated very rapidly. But, due to the angular momentum of Pluto and Charon, this scenario is impossible (Stern 43).

In 1984, Bill McKinnon of Washington University in St. Louis proposed another theory to explain the formation of Charon. According to McKinnon, Pluto and Charon formed as independent bodies and then collided. McKinnon backs up his theory with "the similar masses of Pluto and Charon, the 17 degree tilt of Pluto's orbit, the eccentricity of Pluto's orbit and the fact that both Pluto and Charon rotate on their sides as Uranus does, with their rotation axes lying in the plane of their orbit. Pluto's orbital eccentricity may be related to the force of the collision between Pluto and Charon" (Stern 43).

Unfortunately, McKinnon's theory has one major pitfall. The odds of two tiny planets in our immense solar system colliding are less than one in one million. If Pluto and Charon were the only two planetary bodies in the outer solar system, it would have taken a great cosmic coincidence for Pluto and Charon to collide within a period of 4.5 billion years (Stern 43-44).

One piece of evidence presented to prove McKinnon's theory involves the idea that there may have been more planetary bodies in the outer region of the solar system when Neptune and Uranus were forming. To improve the odds of Pluto and Charon colliding to 50/50, there would have to have been about 1,000 bodies within a region of 20 to 30 AU from the Sun. It does, at first, seem to be strange to think that there were thousands of tiny Pluto-like planetesimals forming when the planets were forming, but the possibility is not so outlandish as to be discarded. There is evidence that there must have been about 100 Earth masses of matter present in the Neptune-Uranus region when they were in the beginning stages of accretion. Uranus and Neptune account for 38 Earth masses of matter. Even one thousand Pluto-like planetesimals would account for only two Earth masses of matter. Thus, the idea that there may have been 1,000 other icy planetesimals is not so far-fetched after all (Stern 44).

More conclusive evidence for the presence of a multitude of icy planetesimals involves Neptune's moon Triton. Triton revolves around Neptune in a retrograde orbit. This is a tell-tale sign that Triton was captured by Neptune. Planetary scientists have studied different methods of capture and keep returning to the fact that, unless there were several hundred planetesimals orbiting the Sun within a 20 to 30 AU region, it is not probable that Neptune could have captured Triton (Stern 44-45).

More evidence to back up the idea that there were thousands of icy planetesimals present within a region 20 to 30 AU from the Sun comes from a study of the tilts of Uranus (98 degrees to its orbital plane) and Neptune (30 degrees to its orbital plane). According to Alastair Cameron, and other scientists from the Harvard-Smithsonian Center for Astrophysics, the tilts of Uranus and Neptune could have only been caused by collisions from planetary bodies with masses between 0.2 and five Earth masses. To make such collisions probable, there had to have been at least 50 such bodies (Stern 45).

Though the size of these planetary bodies is larger than the proposed bodies in the first two pieces of evidence, the need for planetary bodies, excluding Pluto, Charon, Uranus, Neptune and Triton, to have existed is inescapable. In this scenario, Pluto, Charon and Triton are bodies left over from the early existence of a multitude of bodies just like them. The reason that they still exist, while the other bodies are no longer present, is that they were protected by Neptune.

Triton is firmly within Neptune's gravitational grasp and the Pluto-Charon pair move in resonance with Neptune (Stern 45).

Pluto orbits the Sun at an average distance of 39.44 AU. Its orbit ranges from 29.7 AU to 49.3 AU from the Sun. Due to Pluto's great distance from the Sun, its maximum temperature never reaches higher than 60 degrees Kelvin (-213 degrees Celsius) (Zeilik 241). From the polar regions to the middle latitudes, Pluto's surface is covered in a layer of methane ice. In its equatorial region, Pluto's surface is dark red (Engelbrektson 198). Also included in Pluto's surface composition are nitrogen ice and carbon monoxide ice (Zeilik 241). Charon is believed to have a dark gray surface consisting of water ice (Engelbrektson 198). Pluto's atmosphere is estimated to be 600 kilometers thick. It is made of nitrogen, carbon monoxide and methane gas (Zeilik 241).

By studying the variances in the patches of ice on Pluto's surface, astronomers have concluded that Pluto has a rotation period of approximately 6.4 Earth days (Zeilik 241).

Pluto is probably the most mysterious planet in our solar system. No spacecraft has ever flown by Pluto, and cameras have never seen its surface. "More than three billion kilometers away, Pluto patrols the outer reaches of the solar system, guards its secrets well, and challenges us to explore it" (Croswell 36).

Chapter 9

Extrasolar Planets

"Is our solar system alone in the universe?" This question has been asked by countless scientists throughout history. Men have been imprisoned or put to death for believing that our solar system is not the only one in the universe. Almost 400 years ago, the Italian philosopher Giordano Bruno wrote about "numberless Earths circling around their Suns, no worse and no less inhabited than this globe of ours" (Finley 90). The Catholic Church burned him at the stake for heresy because of his belief. Today, Bruno's idea is not thought of as far-fetched or heretical (Finley 90).

In February of 1990, Aleksander Wolszczan of the Arecibo Observatory and Dale Frail of the National Radio Astronomy Observatory began a search for millisecond pulsars (Bruning, Lost and Found 36).

A millisecond pulsar is "a neutron star that emits radio pulses hundreds of times each second" (Bruning, Lost and Found 36). They are "the super-dense remnants of large stars that have exploded as supernovae" (Burnham and Sorathia 32). Using the 305-meter radio telescope at Arecibo, Puerto Rico, Wolszczan and Frail began their search. They succeeded in finding two new millisecond pulsars: PSR 1257+12 and PSR 1534+12 (Bruning, Lost and Found 36).

Pulsars emit radio pulses with such a remarkable regularity, that they surpass the precision of all but the most accurate of man-made clocks. In fact, they are so regular that the period of their radio pulses can be measured by astronomers to a tiny part of one-trillionth of a second. If a pulse arrives even one-trillionth of a second out of sync, then there is no doubt that the pulsar being studied is very different from others (Bruning, Lost and Found 36).

In the constellation Scutum, PSR 1257+12 showed signs of behavior unusual for a pulsar (Bruning, Desperately Seeking 37). Wolszczan and Frail found that the radio pulses emitted by PSR 1257+12 occasionally arrived up to 15 trillionths of a second before or after the expected time of arrival! With this exciting discovery, Wolszczan and Frail went to the Very Large Array (VLA) near Socorro, New Mexico, to study PSR 1257+12's pulse arrival times. Their research at VLA showed the same discrepancies in the pulse arrival times that their data from Arecibo showed (Bruning, Lost and Found 36).

After careful evaluation of their data, in 1992 Wolszczan and Frail began to believe they had evidence that PSR 1257+12 was part of a planetary system. They came to this conclusion because "The simplest and most likely explanation for the variation [in the arrival times of the radio pulses from PSR 1257+12] is that two or three companions pull on the star as they revolve around it" (Bruning, Lost and Found 36).

In our solar system, the Sun revolves around a point called the barycenter or center of gravity. This occurs because of the gravitational forces exerted on the Sun by the planets in orbit around it. From the variations in PSR

1257+12's pulse arrival times, Wolszczan and Frail were able to determine many things. At a speed of 0.7 meters second, PSR 1257+12 revolves around its barycenter with a radius of approximately 900 kilometers. It gives off 160.8 pulses every second. Though the actual mass of PSR 1257+12 is not known, it is assumed to be 1.4 solar masses because that is the average mass of most millisecond pulsars (Bruning, Lost and Found 36).

Wolszczan and Frail were also able to draw many conclusions about the supposed planetary bodies orbiting PSR 1257+12. They determined the rotation periods of its companions and calculated the orbital radii and masses of its companions. According to their calculations, Planet One has an orbital radius of 0.36 AU, a mass of at least 3.4 Earth masses and a period of 66.6 days. The orbital radius, mass and period of Planet Two are, 0.47 AU, at least 2.8 Earth masses and 98.2 days, respectively. Planet Three's orbital radius and period are 1.1 AU and 355 days, respectively; its mass is unknown (Bruning, Lost and Found 36).

On Friday, February 25, 1994, the existence of proposed planets One and Two was confirmed. Frederic Rasio, a theoretical astrophysicist at the Institute for Advanced Study in Princeton, New Jersey said, "We know absolutely for sure now that there are planets there" ("Scientists" 3A).

Planets One and Two and, if it exists, Three are considered second generation planets. Astronomers currently believe that a supernova explosion from a more massive star in a binary star (two star) system created PSR 1257+12. The second star making up the binary system is believed to have evaporated as a result of PSR 1257+12's intense radiation, which caused a disk of gas to form around PSR 1257+12, and it is from this disk the planets are thought to have accreted (Bruning, Desperately Seeking 37).

Astronomers have continued to seek out star systems capable of sustaining planets. Direct searches have not yet led to the discovery of any more extrasolar planets. However, indirect searches may have given astronomers some success. They have discovered dust disks surrounding as many as 60% of the young stars known to exist in the Milky Way. These disks of gas resemble the disk astronomers believe once surrounded our Sun and from which our solar system formed. Some of the stars astronomers have found dust disks around are HL Tauri, GU Orionis, 51 Ophiuchi, DG Tauri, Vega and L1551-IRS5. These disks are at least as massive as 0.01 times the mass of our Sun. On summer evenings, the brightest star we see near the Zenith is Vega (Beckwith and Sargent 27). It has a disk twice as large as our solar system which contains particles approximately one millimeter in size (Bruning, Indirect 38).

Older stars have more tenuous disks of dust. By studying older stars and the reactions they have on their surrounding dust disks, astronomers have been able to learn different things about how the Sun cleared our solar system of extra matter once planets had formed. Dust disks surrounding stars generally evolve over a few million years and dissipate after 10 million years. Thus, planetary formation takes place within an estimated 10 million year time period. However, not all dust disks are able to form planets during this "required" time period. FU Orionis, for instance, produces strong flares which prevent planet formation by pushing the disk away (Bruning, Indirect 38).

One star which has a great possibility of having a planetary system forming around it is Beta Pictoris. It lies 56 light-years from our Sun (Bruning, Indirect 38), and is a few hundred million years old (Beckwith and Sargent 27). In 1983, the Infrared Astronomical Satellite discovered the Beta Pictoris' dust disk (Folger 27) reaching more than 1000 AU outward. Its mass is less than 0.00001 solar masses (Beckwith and Sargent 27), and it is approximately 10 times the size of our solar system (Bruning, Indirect 38). In 1991, when astronomers used the Hubble Space Telescope to view Beta Pictoris. Through Hubble, they saw the structure of the dust disk much more clearly than they had with ground based telescopes. By using a high-resolution spectrograph, Hubble showed astronomers that the disk around Beta Pictoris actually consists of two rings. The outer ring is made of small, solid particles, and is spread outward from Beta Pictoris over billions of miles. Inside this ring is a second ring which is made of diffuse gas and lies within a few hundred million miles of Beta Pictoris (Folger 27).

How the disks formed or what created them is unknown. According to Albert Bogges of NASA's Goddard Space Flight Center, "It's possible that it [the gas ring] was shed by Beta Pictoris. But what I suspect is that the gas comes from the ring of solid particles" (Folger 27). His theory is that the gas ring is a result of the collisions between the solid particles in the outer ring. It is thought that the solid particles may be in the process of accretion. At this point, the planetesimals thought to be forming are still to small too be seen (Folger 27).

The Hubble Space Telescope has also detected solid clumps of matter in the gaseous inner ring around Beta Pictoris. The clumps viewed by Hubble have been detected spiraling toward Beta Pictoris the same way comets spiral when they have been diverted from their original paths by close encounters with forming protoplanets (Folger 27).

The collisions described above follow the same pattern that is thought to have been followed in the creation of our planets. They are similar to the collisions which may have created the atmospheres and oceans which currently exist, or may have existed at one time, on many of our planets (e.g. Earth, Venus, Mars). "At the very least we can say that Beta Pictoris is similar to a very early phase of our own solar system; whether it will go the way of our solar system is another question," says Albert Bogess (Folger 27).

In the mid-1980's Anneila Sargent, Senior Research Associate in Astronomy at the California Institute of Technology and Associate Director of the Owens Valley Radio Observatory; and Steven Beckwith, Director of the Max Plank Institute for Astronomy in Heidelberg, Germany, were part of a team that made some exciting discoveries about another star. The star HL Tauri, from the constellation Taurus, is classed as a T-Tauri star (Beckwith and Sargent 27).

T-Tauri stars are young solar-mass objects which have properties akin to those our Sun had during its early years. They are typically between 100,000 and 10,000,000 years old and tend to radiate infrared rays in excessive amounts. This excessive radiation and the fact that T-Tauri stars have evolved enough to be seen without the use of non-optical telescopes, tell astronomers that "[T-Tauri stars] are surrounded by remnants of the nebular material from which they formed." All of these characteristics point astronomers to the fact that T-Tauri stars are suitable for planetary formation (Beckwith and Sargent 27).

HL Tauri is surrounded by a gaseous disk which is approximately 2,000 AU wide and has a mass of approximately 0.10 solar masses. These figures show that HL Tauri's disk is not only more massive than the one surrounding Beta Pictoris, but it is also more than sufficient to support planetary formation. The figures also fit with the characteristics astronomers believe the primitive Sun had when planets were beginning to form (Beckwith and Sargent 27).

Older stars do not have the large disks associated with young stars because their disks have evolved over millions of years. One characteristic of their evolution is the presence of gaps in their disks. For instance, Beta Pictoris and GM Aurigae (another old star) have gaps in their disks (Beckwith and Sargent 28).

In GM Aurigae's disk, there is a gap extending 0.3 AU outward from the center. This is about the same distance as the distance between Mercury and our Sun. By looking at GM Aurigae's spectral energy, astronomers have discovered that each "low flux" gap in GM Aurigae's disk lies in the same wavelength range as some of the planets in our solar system (Beckwith and Sargent 28).

From calculations, observations and research involving stars in the Taurus-Auriga region, "it appears that at least one half of all nearby young stars have the potential to become planetary systems" (Beckwith and Sargent 28).

"In 1983 a consortium of American, Dutch and British scientists launched the Infrared Astronomical Satellite (IRAS). One of the first things it discovered was systems of solid particles in orbit around more than a dozen mature nearby stars" (Beckwith and Sargent 24). In 1986 interferometric telescope arrays began producing maps of gaseous, planet forming disks. In the same time frame, the

IRAM consortium of French, German and Spanish radio-astronomers built a 30-meter telescope at Pico Veleta, Spain. Within the first two years of its operation, the 30-meter telescope discovered nebulae circling almost half of the 100 stars it observed (Beckwith and Sargent 24). On March 30, 1993, astronomers found a disk circling the star Fomalhaut, 22 light-years from our Sun. The disk they discovered greatly resembles the disk around Beta Pictoris and the disk that astronomers believe surrounded our Sun and gave birth to our planets ("Circumstellar Disk" 13-14).

With all of these discoveries and the continuing work of astronomers around the world, our solar system is becoming less and less of an enigma. "Ten years ago, it was possible to argue that the solar system is unique. Today the evidence strongly suggests that planetary systems are abundant in the Galaxy" (Beckwith and Sargent 29). It is impossible to predict what discoveries we will witness ten years from now. The possibilities are as diverse and exciting as our vast and beautiful universe.

APPENDICES

Appendix Table 1: Astronomical Constants

NAME	CONSTANT
Earth mass (em)	= 5.974×10^{24} kg
Solar mass (sm)	= 1.989×10^{30} kg
Light year (ly)	= 9.4065×10^{15} m = 6.234×10^{4} AU
Astronomical unit (AU)	= $1.495978706 \times 10^{11}$ m

(Arny A-2)

Appendix Table 2: Physical Properties of the Planets

PLANET	RADIUS (Eq) (Earth Units)	RADIUS (Eq) (km)	MASS (Earth Units)	AVG DENSITY (gm/cm^3)
Mercury	0.382	2,439	0.055	5.43
Venus	0.949	6,051	0.815	5.25
Earth	1.00	6,378	1.00	5.52
Mars	0.533	3,397	0.107	3.93
Jupiter	11.19	71,492	317.9	1.33
Saturn	9.46	60,268	95.18	0.71
Uranus	3.98	25,559	14.54	1.24
Neptune	3.81	24,764	17.13	1.67
Pluto	0.176	1,123	0.00256	between 1.89 and 2.14

(Arny A-2)

Appendix Table 3: Orbital Properties of the Planets

PLANET	DISTANCE FROM SUN (AU)*	PERIOD YEARS	PERIOD DAYS	ORBITAL INCLINATION**	ORBITAL ECCENTRICITY
Mercury	0.387	0.2409	87.97	7.00	0.206
Venus	0.723	0.6512	224.7	3.3915	0.007
Earth	1.00	1.0	365.26	0.00	0.017
Mars	1.524	1.8809	686.98	1.85	0.093
Jupiter	5.203	11.862	332.59	1.31	0.048
Saturn	9.539	29.4577	10759.22	2.49	0.056
Uranus	19.19	84.014	30685.4	0.77	0.046
Neptune	30.06	164.793	60189.0	1.77	0.010
Pluto	39.53	247.7	90465.0	7.15	0.248

*Semi-major axis of the orbit.

**With respect to the ecliptic.

(Arny A-2)

Appendix Table 4: Planetary Rotation Rates and Inclinations

PLANET	ROTATION PERIOD (equatorial)	INCLINATION OF EQUATOR TO ORBITAL PLANE
Mercury	58.65 days	0°
Venus	243.01 days **R**	117° 18′
Earth	23h 56min 4.1s	23° 27′
Mars	24h 37min 22.6s	25° 12′
Jupiter	9h 50min 30s	3° 07′
Saturn	10h 14min	26° 44′
Uranus	17h 14min **R**	97° 52 ′
Neptune	16h 3min	29° 34′
Pluto	6.39 days **R**	98°

R: Retrograde orbit (Zeilik A-4)

Appendix Table 5: Satellites of the Solar System

PLANET SATELLITE	RADIUS (km)	ORBITAL PERIOD (days)	MASS (10^{20} kg)	DENSITY (g/cm^3)
Earth				
Moon	1738.0	27.322	734.9	3.34
Mars				
Phobos	13x11x9	0.319	1.3x10^{-4}	2.2
Deimos	8x6x5	1.263	1.8x10^{-5}	1.7
Jupiter				
Metis	20.0	0.295	9.0x10^{-4}	-
Adrastea	13x10x8	0.298	1.0x10^{-4}	-
Amalthea	135x82x75	0.498	8.0x10^{-2}	3.00
Thebe	55x?x45	0.6745	1.4x10^{-3}	-
Io	1821.0	1.769	893.3	3.57
Europa	1565.0	3.551	479.7	2.97
Ganymede	2634.0	7.155	1482.0	1.94
Callisto	2403.0	16.689	1076.0	1.86
Leda	~8.0	238.7	4.0x10^{-4}	-
Himalia	92.5	250.6	8.0x10^{-2}	~1.00
Lysithea	~18.0	259.2	6.0x10^{-4}	-
Elara	~38.0	259.7	6.0x10^{-3}	-
Ananke	~15.0	631.0**R**	4.0x10^{-4}	-
Carme	~20.0	692.0**R**	9.0x10^{-4}	-
Pasiphae	~25.0	735.0**R**	1.6x10^{-3}	-
Sinope	~18.0	758.0**R**	6.0x10^{-4}	-
Saturn				
Pan	10.0	0.574	4.2x10^{-6}	-
Atlas	19x?x14	0.602	1.6x10^{-4}	-
Prometheus	74x50x34	0.613	5.0x10^{-3}	-
Pandora	55x44x31	0.629	3.4x10^{-3}	-
Epimetheus	69x55x55	0.694	5.6x10^{-3}	-
Janus	97x95x77	0.695	2.0x10^{-2}	-
Mimas	210x197x193	0.942	0.370	1.17
Enceladus	256x247x244	1.370	1.2	1.24
Tethys	536x528x526	1.888	6.17	1.26
Calypso	15x8x8	1.888	4.0x10^{-5}	-
Telesto	15x13x8	1.888	6.0x10^{5}	-
Dione	559.0	2.737	10.8	1.44
Helene	18x?x<15	2.737	1.6x10^{-4}	-
Rhea	764.0	4.518	23.1	1.33
Titan	575.0	15.945	1345.5	1.88
Hyperion	180x140x112	21.277	0.28	-
Iapetus	718.0	79.331	15.9	1.21
Phoebe	115x110x105	550.4**R**	0.1	-

(Arny A-5; Zeilik A6-A7)

Appendix Table 6: Satellites of the Solar System cont.

PLANET SATELLITE	RADIUS (km)	ORBITAL PERIOD (days)	MASS (10^{20} kg)	DENSITY (g/cm^3)
Uranus				
Cordelia	13.0	0.336	$1.7x10^{-4}$	-
Ophelia	16.0	0.377	$2.6x10^{-4}$	-
Bianca	22.0	0.435	$7.0x10^{-4}$	-
Cressida	33.0	0.465	$2.6x10^{-3}$	-
Desdemona	29.0	0.476	$1.7x10^{-3}$	-
Juliet	42.0	0.494	$4.3x10^{-3}$	-
Portia	55.0	0.515	$1.0x10^{-2}$	-
Rosalind	29.0	0.560	$1.5x10^{-3}$	-
Belinda	33.0	0.624	$2.5x10^{-3}$	-
Puck	77.0	0.764	$5.0x10^{-3}$	-
Miranda	240x234x233	1.413	0.66	1.26
Ariel	581x578x578	2.520	13.5	1.65
Umbriel	584.7	4.144	11.7	1.44
Titania	788.9	8.706	35.2	1.59
Oberon	761.4	13.463	30.1	1.50
Neptune				
Naiad	29.0	0.296	$1.4x10^{-3}$	-
Thalassa	40.0	0.312	$4.0x10^{-3}$	-
Despina	74.0	0.333	$2.1x10^{-3}$	-
Galatea	79.0	0.396	$3.1x10^{-2}$	-
Larissa	104x?x89	0.554	$6.0x10^{-2}$	-
Proteus	218x208x201	1.121	0.6	-
Triton	1352.6	5.875	214.0	2.0
Nereid	170.0	360.125	0.31	-
Pluto				
Charon	593.0	6.387	11.0	1.0?

(Arny A-5; Zeilik A6-A7)

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