

## Chapter 14: Formation of Planetary Systems

Chapter 12 discussed the process by which stars form from a cloud of gas and dust. The result is a central star surrounded by a disk also made of gas and dust. This chapter describes the theory of how such a disk becomes a system of planets, moons, dwarf planets, asteroids, and comets like our solar system.

We will apply the theory mainly to our solar system, since it is the planetary system that we can observe in the most detail. We might then ask how long ago the solar system formed. The most accurate method to determine the age of one of its members, the Earth, is to use radioactive dating from the relative abundances of radioactive atomic nuclei and their decay products (see Ch. 8). The nucleus most widely used for this purpose is uranium-238 ( $^{238}_{92}\text{U}$ ), which decays to thorium-234 ( $^{234}_{90}\text{Th}$ ) with a half-life of 4.468 billion years (Gyr). Geologists have used radioactive dating to determine that zircon crystal in the Earth's oldest known crust, in western Australia, is 4.4 Gyr old. This is a lower limit on the age of our planet, since the Earth must have formed before the rocks now found on its surface. Rocks from the Moon that were collected and returned to Earth by astronauts have also been found to be 4.4 Gyr old. The other source of solid material from the solar system, meteorites, are as old at 4.6 Gyr. We can therefore conclude that the age of the solar system is about 4.6 Gyr.

### The Formation of Planets from a Disk of Gas and Dust

As noted in Chapter 2, the planets all move in the sky along nearly the same circular path that the Sun follows, through the constellations of the ecliptic, often called the zodiac. This means that their orbits are all in nearly the same plane, as shown in Figure 3-2. In order for this to happen, the planets must have formed from a flat structure. Given our ideas about star formation, this structure should be the disk that surrounded the newly-formed Sun. If so, many other stars should have planets as well.

We can measure the masses of planets by the orbits of their moons or, for moonless Mercury and Venus, by their gravitational influence on space probes that pass by or orbit them. We can then divide by their volumes to determine the density and infer the physical condition of the matter that composes them. We find that the inner four, terrestrial planets – Mercury, Venus, Earth, and Mars – are combinations of rocky material and metals. The much more massive outer planets have average densities so low that they must be composed mostly of gases, although each probably contains a relatively small, rocky core. Many of the moons of the outer planets, as well as the dwarf planets in the outer solar system, *e.g.*, Pluto, are composed mostly of water and other ices (*e.g.*, carbon-dioxide and methane ice).

From these data, we infer that the disk was not initially uniform in composition. Initially, the inner, denser portion of the disk was much hotter than the outer regions both from the heat of contraction and from absorption of light from the newly formed Sun. The temperature ranged from a few thousand K at 0.1 AU to about 100 K at 10 AU. In the regions close to the Sun, the heat broke up the grains of dust, the ice vaporized, and the molecules broke apart into individual atoms. The light hydrogen and helium atoms had relatively high velocities, since the velocity of an atom at any given temperature is inversely proportional to the square-root of its mass. (We can see this by solving for  $v$  in eq. 7-1.) Most of these atoms escaped to beyond 5 AU, leaving primarily heavier elements in the inner region. This process is called differentiation, which in general means that the structure develops such that its basic physical properties depend on distance from the center. Eventually, the inner disk cooled by radiating infrared light. This allowed atoms to form molecules again and for molecules involving the heavier elements to form grains of dust. Throughout the disk, the electromagnetic force attracted more atoms and molecules to make larger dust grains. Eventually, macroscopic bodies combined to make chunks of “dirty” ice and loose rocks called planetesimals.

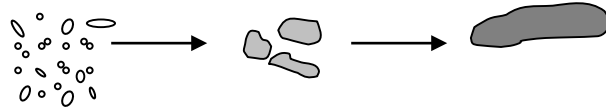


Figure 14-1. Sketch of planetesimal formation from many dust grains (far left) to pebbles (middle) to rocks (right). [Not drawn to scale.]

Each planetesimal had only a little mass, and so it exerted only a slight gravitational force to attract other planetesimals. Nevertheless, this was enough over the years to cause neighboring planetesimals to combine to become larger. As the planetesimals grew, their gravity became stronger. Planetesimals with slightly different orbital semi-major axes orbited the Sun at slightly different speeds. A given planetesimal therefore encountered and combined with “fresh” planetesimals over time (Fig. 14-2). The more massive objects possessed stronger gravity, and so grew faster through this **accretion** of smaller bodies.

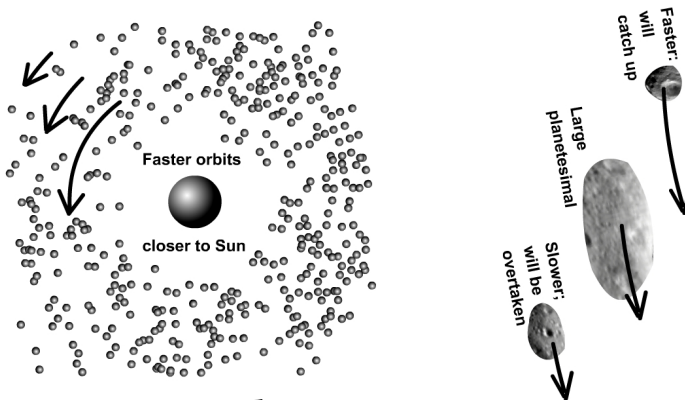


Figure 14-2. Sketch of planetesimals at different orbits around the Sun. Those farther out have slower orbits. As a result, planetesimals pass each other, each time drawing closer because of gravity. [Note: arrows are exaggerated: orbital speeds of nearby orbits are only slightly larger or smaller.]

When a planetesimal grows to about 0.0004 times the Earth’s mass, its self-gravity becomes strong enough to crush it into a sphere. The object can still grow by accreting more planetesimals. The bodies that ended up with the highest masses became planets. Less massive bodies ended up as dwarf planets, moons, asteroids, comets, and meteors. All except the largest of these – dwarf planets and the largest moons – have so little mass that they have irregular rather than spherical shapes.

## Collisions in the Early Solar System

There were probably more planets early in the solar system’s history than the eight that we now find. Near-collisions of the newly formed massive bodies disturbed some of their orbits so that they reached the escape velocity and exited from the Sun’s gravitational influence. Actual collisions also occurred. Based on the similarity between the composition (including ratios of abundances of different isotopes) of material in a terrestrial planet’s mantle – the layer below the outer crust – and Moon rocks brought back by the Apollo astronauts, planetary geologists infer that the Moon was formed from debris following the direct collision of a Mars-sized object and the Earth several tens of millions of years after the Earth formed. The angular momentum of the rotating disk out of which the planets formed should give the planets spin in the same direction. Yet the gas giant Uranus has a rotation axis that is nearly in the plane of the solar system rather than nearly perpendicular, as it is for the other gas giants. A major collision with a very massive body seems the best explanation of how such a massive planet with high angular momentum could have such a strong tilt of its poles. The very slow spin of Venus – once every 243 days – also probably resulted from a collision. It took a few hundred million years for violent collisions of such massive bodies to end and for the solar system finally to settle down to roughly its present state.

The terrestrial planets close to the Sun – Mercury, Venus, Earth, and Mars – are all relatively small and rocky. Their constituent rocks are predominantly silicates, compounds containing silicon (Si) and oxygen

(O) that are rich in iron (Fe), magnesium (Mg), aluminum (Al), and other elements. This is important because silicates are capable of trapping water and other relatively light molecules into their crystal structure even at high temperatures. This allowed these light substances to be released at a later time in a terrestrial planet's history, *e.g.*, through volcanoes.

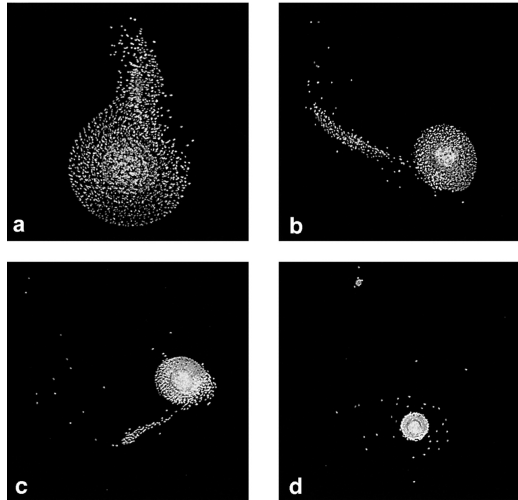


Figure 14-3. Computer simulation of the formation of the Moon after collision between a Mars-sized body and the Earth. The panels show 4 times from just after the collision to full formation of the Moon. [Source: [rimg.geoscienceworld.org](http://rimg.geoscienceworld.org)]

## Evidence for the Theory of Solar System Formation

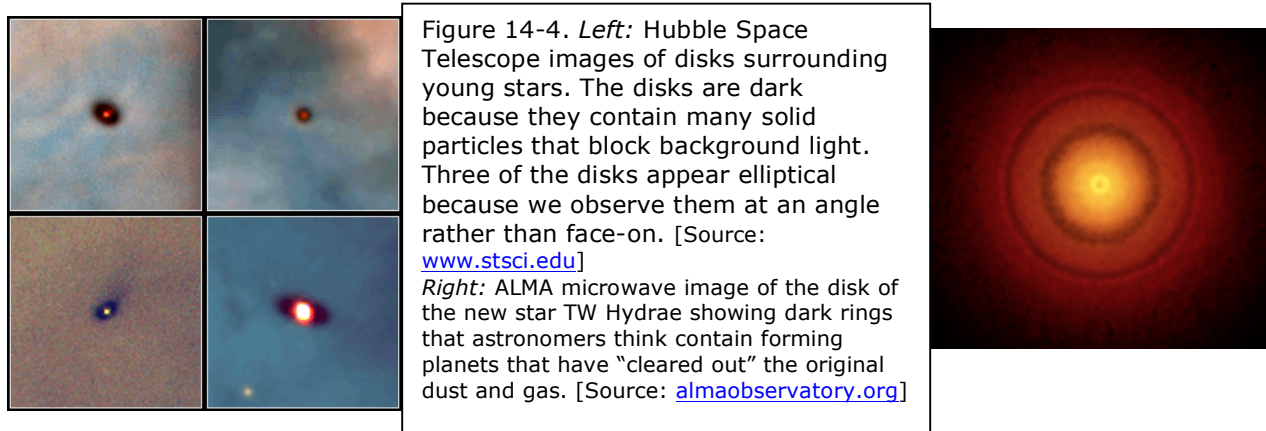
The formation of planets and moons from accretion of smaller bodies in a disk, as part of the star formation process, agrees with a number of observations of our solar system:

1. All planets and most moons orbit counterclockwise around the Sun as viewed down the north pole of the Earth's orbital plane (the ecliptic). This is explained as the direction of rotation of the disk. The majority of planets also spin counterclockwise, suggesting that the planets and moons inherited their angular momentum from the overall disk.
2. Except for the least massive planets (Mercury and Mars) – whose orbits are most easily perturbed by larger planets – planetary orbits are nearly circular. A disk has circular symmetry, so any bodies created from it should move in circular orbits unless their motions are greatly disturbed by near-collisions with other massive bodies.
3. The orbits of the planets lie very close to the same plane (Fig. 3-2), which is also the equatorial plane of the Sun. This is most readily explained if the objects and the Sun were all formed from a thin disk.
4. The physical state and composition of our planetary system is highly differentiated, from the terrestrial inner planets (Mercury, Venus, Earth, and Mars) made from rocks and metals to the gaseous outer planets (Jupiter, Saturn, Uranus, and Neptune). The moons, minor planets, and comets in the outermost solar system are composed of ices. This makes sense if the planets formed from a disk whose temperature decreased with distance from the Sun.
5. Astronomers have observed a number of young stars with disks that surround them (see below).
6. Planets have been detected around many other stars (see below). So, planet formation is common, as it must be if it is a natural consequence of the star formation process.
7. There are still bodies in the solar system that fit the description of planetesimals: asteroids and comets.

The model must also be able to explain the exceptions to the general trends listed above. For example, the rotations (spins) of Venus, Uranus, and Neptune are clockwise rather than counterclockwise, and some moons revolve clockwise around their planets. As discussed above, many of these anomalies could have been caused by glancing collisions by massive planetesimals after most of the planets and moons had formed. Bombardment by such bodies was common during the first several hundred million years of the solar system's existence. Others can be explained by the effects of the weak – but non-negligible over time – gravitational influence of other planets and moons.

## Disks and Planets around Other Stars

Astronomers have discovered disks around a number of young stars. Based on how they reflect the light from the star, scientists conclude that the disks are composed of planetesimals. Figure 14-4 presents images of four such disks.



Evidence for the existence of planets around stars other than the Sun comes mainly from measuring to ultra-high accuracy the wavelengths of the absorption lines in the spectra of stars. If another body is in orbit around the star, the star will also orbit around the center of mass of the system. This orbital velocity can be detected by measuring a back-and-forth Doppler shift in the wavelengths of the lines. In the case of our solar system, the center of mass of the solar system is inside the Sun, so the size of the Sun's orbit is small. The period, equal to Jupiter's orbital period of 11.9 yr, is long, so the Sun's velocity is very low. The presence of planets around the Sun would therefore be exceedingly difficult to detect with this method if observed from other star systems with our current techniques. However, in systems that contain stars less massive than the Sun, with planets that are at least as massive as Saturn with orbits close to their stars, the Doppler shift is significant enough to detect, even though the velocities are only tens of km/s (see Fig. 14-5 for an example).

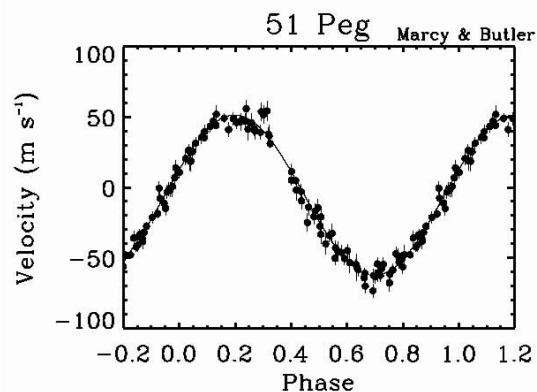


Figure 14-5. The line-of-sight component of the velocity vs. time curve of a star (51 Pegasi) with a planet orbiting around it. The planet's gravity causes the star to execute a small orbit about the center of mass of the system. The velocity is measured from the changing Doppler shift of the absorption lines in the star's spectrum. Recall that a negative velocity means that the star is moving toward us and positive is away from us. [Source: [www.exoplanets.org](http://www.exoplanets.org)]

Another method for detecting candidate exoplanets is to look for the signs of a transit – a partial eclipse when the planet, in its orbit, passes between the Earth and the planet’s star. This causes the brightness of the star to decrease slightly, by an amount that depends on the ratio of the diameter of the planet to the diameter of the star, once per orbit. However, only a small fraction of planetary orbits are aligned with our line of sight so that such a transit occurs. Astronomers therefore need to monitor the brightness of many stars for at least a few years to detect and confirm the transits. When they observe this phenomenon, the size of the planet can be determined, since the diameters of different types of stars are known and the decrease in brightness gives the ratio of the planet’s diameter to that of the star. This has been the mission of the *Kepler* satellite observatory launched by NASA in 2009. Well over 1000 such extra-solar planets – **exoplanets** – have been detected thus far by this method. Some of these are not much larger than the Earth, orbiting in the **habitable zone** (where temperatures are in the range where liquid water can be abundant) of the planetary system.

The formation of planets is therefore quite common. The star system whose data are shown in Figure 14-5 contains a planet with roughly the mass of Jupiter and an orbital period of 4.2 days. From the period – plus the mass of the star, which is similar to that of the Sun – astronomers can calculate the distance of the planet from the star using Kepler’s 3rd Law (see Ch.3) to be 0.05 AU.

This raises the question of what a planet so massive – presumably a gas giant – is doing so close to its parent star. Computer simulations demonstrate that it should, in fact, be common for massive planets to migrate significantly from their site of formation after they have formed. This obviously did not happen in our solar system. But the simulations indicate that it probably would have occurred if more than one Jupiter-sized planet had formed, because of their non-negligible gravitational influence on each other. The detection of massive exoplanets with orbits close to low- or medium-mass stars using Doppler shifts is possible, whereas lower-mass planets with larger orbits have too small an effect on their stars to allow detection. This selection effect explains why nearly all of the exoplanets found thus far are very massive and have small orbits.

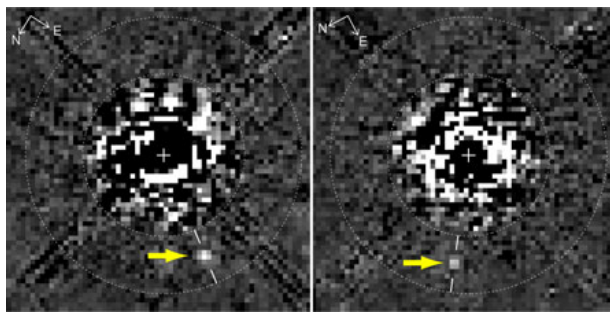


Figure 14-6. Hubble Space Telescope images, obtained at two different times, of an extrasolar planet, marked by the arrows. The light from the star is mostly blocked out by a disk placed in the optics. [Source: stsci.edu]

Another aspect of planet formation that has been difficult to understand is that the process appears to occur more rapidly than predicted: evidence of planets (e.g., dark rings in disks – see Fig. 14-4, right side) in systems younger than about 1 million years rather than 10 million years or more, as predicted by the theory discussed above. More work is obviously needed before scientists can claim to understand how planetary systems are produced around new stars.

Direct imaging of exoplanets is exceedingly difficult because the glare of its star outshines it by so much. However, techniques for blocking or subtracting the star’s light are advancing. Figure 14-6 shows such a direct image obtained with the Hubble Space Telescope.

A statistical study has found that stars with higher abundances of heavy elements are more likely to be observed to have planets orbiting around them. This supports the model of planet formation from a disk that starts out with dust containing such elements, as well as gas.



## Differentiation of the Interiors of Terrestrial Bodies

During the first few hundred millions of years after the planets formed, the solar system was a rather chaotic place. Planets frequently collided with the many leftover planetesimals that moved in elliptical orbits throughout the solar system. The energy from these collisions, as well as the contraction of the planets from their self-gravity and energy deposited from radioactive decays in their interiors, heated the planets and other bodies to high temperatures. This melted the terrestrial planets, moons, and asteroids. As a consequence, the heavier metals — iron and nickel being the most common — sank to form liquid metal cores in the their centers (Fig. 14-7). The remaining rocky compounds formed surrounding regions called mantles.

After differentiation, the terrestrial planets cooled and solidified. The rate of cooling depends on the planet's size. The main loss of heat is by radiation of infrared light into space, the rate of which equals the luminosity, which is proportional to the square of the radius of the planet (see Ch. 5). The amount of mass that needs to be cooled, however, goes as the cube of the radius (*i.e.*, as the volume). Therefore, larger planets take longer to cool. Larger planets also have more heat production in their interiors from the decay of radioactive atoms with long half-lives that were part of the material out of which the planet formed.

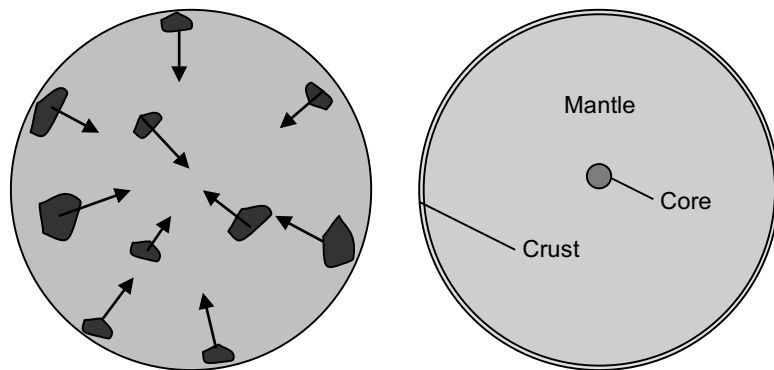


Figure 14-7. Differentiation of the interior of a terrestrial body. *Left:* Early in its history, the planet is so hot that the metals and rocky material are in a liquid (molten) state. Condensations with higher densities of relatively heavy metals, especially iron and nickel, sink toward the center to form the core. The less dense rocky material — compounds of silicon, etc. — remain closer to the surface, forming the mantle. *Right:* The basic structure of the body after differentiation.

The cooling terrestrial planet formed a solid crust on its outer shell while its interior cooled more slowly. Any of the heavier metals that are present in the crust today were brought by planetesimals — meteors and larger bodies — that crashed into the surface after crust formation. On the Earth — which, because of its size, still has a hot, partially molten interior — the crust floats on a semi-liquid layer. This causes slow (centimeters per year) continental drift and various geological phenomena such as volcanoes and earthquakes.

## Planets with Atmospheres

Whether a planet can maintain a substantial atmosphere depends on two critical factors: the temperature, influenced mainly by distance from the Sun, and the surface gravity, determined by the mass and radius of the planet. Essentially, the temperature needs to be low enough so that the average random velocity of the atoms and molecules is much less than the escape velocity (eq. 4-14). Equation 7-1 indicates that the average random velocity varies inversely with the square-root of the mass of the atom or molecule. This implies that, if a planet is close to the Sun and therefore has a relatively high temperature, it cannot keep an atmosphere composed of the lightest elements, hydrogen and helium. Instead, any atmosphere possessed by such a planet will be dominated by heavier atoms and molecules, such as  $N_2$  and  $O_2$  (Earth) or  $CO_2$  (Venus and Mars). Farther from the Sun, atmospheres rich in hydrogen and helium are expected.

The differentiation of the disk prior to planet formation removed most of the hydrogen and helium gas from the inner solar system out to about 5 AU. From about this distance to 30 AU from the Sun, most of the mass was still contained in these two elements, so planets that formed there became gas giants. Their centers are thought to contain rocky cores around which the gas accumulated. The self-gravity of the gas giants is sufficient to retain these original atmospheres, given the relatively cold temperatures that far from the Sun. Jupiter, Saturn, Uranus, and Neptune therefore maintain enormous atmospheres composed mostly of hydrogen – much of which is in the form of molecules, *e.g.*, H<sub>2</sub>, methane (CH<sub>4</sub>), and ammonia (NH<sub>3</sub>) – and helium.

Because the terrestrial planets are all too small and close to the Sun to have kept most of their original H and He atoms, their atmospheres must have been produced at a later stage. The main source is outgassing from volcanoes. This produces an abundance of nitrogen and water, plus carbon-dioxide and methane. The oxygen in the atmosphere, however, comes from living organisms – initially cyanobacteria (blue-green algae) and, during more recent epochs, various kinds of plant life. Because oxygen reacts readily with metals such as iron, it cannot be a major constituent of the atmosphere of a planet in the absence of a process, such as photosynthesis, that replenishes it.

The presence of a substantial atmosphere can raise the surface temperature of a planet through the greenhouse effect. Certain molecules, especially carbon-dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>), are efficient absorbers of infrared light, but allow visible light to pass through. Since the bulk of the energy in sunlight is in visible light, most of this energy can reach the ground. The planet's surface, however, has a temperature of hundreds of Kelvins, and so cools by emitting blackbody radiation at infrared wavelengths. If some of that infrared light is absorbed by greenhouse gases, then it does not leave the planet and therefore the heat remains. Instead, the atmosphere and surface heat up until the amount of energy in blackbody radiation that escapes the atmosphere equals the amount of energy received in sunlight. This occurred to such an extent on Venus that the surface of the planet now has a temperature of 740 K, hot enough to melt lead. Venus contains a high abundance of CO<sub>2</sub> in its atmosphere, hence the strong greenhouse effect. Carbon-dioxide dissolves in liquid water, which causes much of the CO<sub>2</sub> on the Earth to be confined to the oceans. Venus is too close to the Sun to keep water in liquid form, so all of its CO<sub>2</sub> is part of its atmosphere.

## Close-up View of Our Solar System

Space probes and powerful telescopes have explored many of the worlds in our solar system. Figures 14-8 to 14-14 presents some of the images obtained with these instruments.

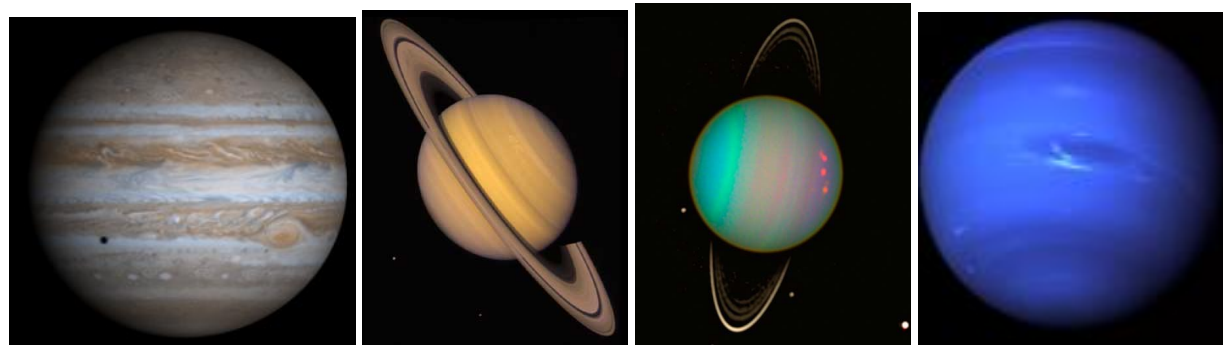


Figure 14-8. The gas giant planets (from left) Jupiter, Saturn, Uranus, & Neptune. [Source: nasa.gov]

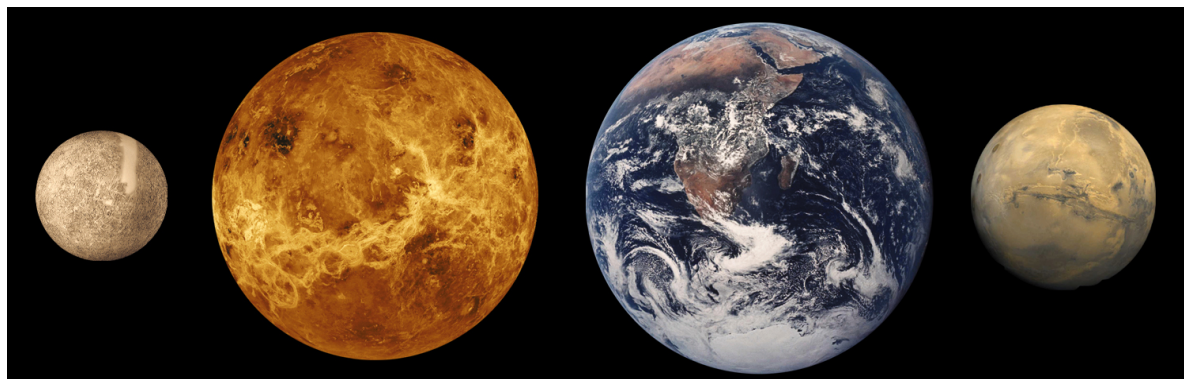


Figure 14-9. The terrestrial planets (from left) Mercury (composite; blank streak is where no image is available), Venus (radar image; colors are educated guesses), Earth, & Mars. [Source: nasa.gov]



Figure 14-10. *From left:* The Earth's Moon, Phobos & Deimos (Mars), and the dwarf planet Pluto. [Source: nasa.gov]

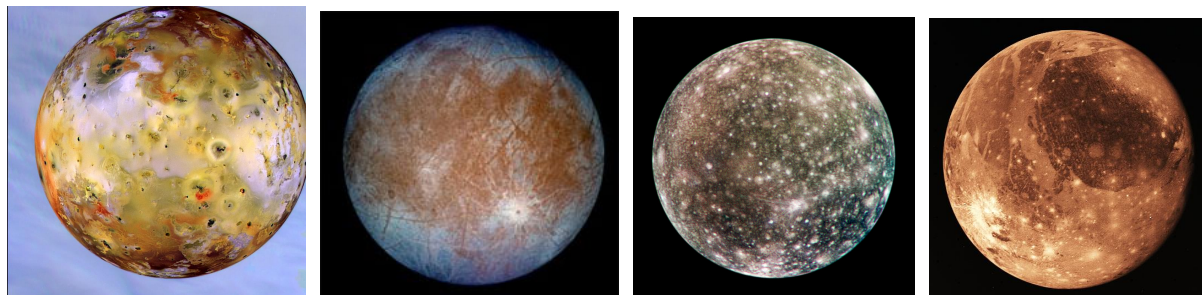


Figure 14-11. Jupiter's four large moons (from left) Io (splotches are volcanoes), Europa (showing cracks in its icy surface), Callisto, & Ganymede. [Source: nasa.gov]

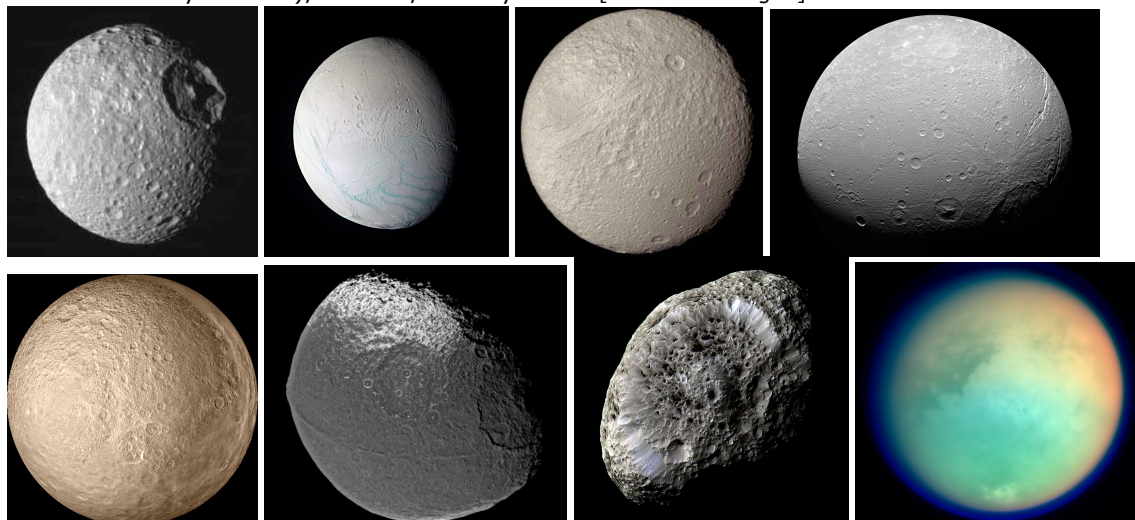


Figure 14-12. Saturn's 8 largest moons (top from left) Mimas, Enceladus, Tethys, Dione, (bottom from left) Rhea, Iapetus, Hyperion, and Titan (colored haze is its atmosphere). [Source: nasa.gov]



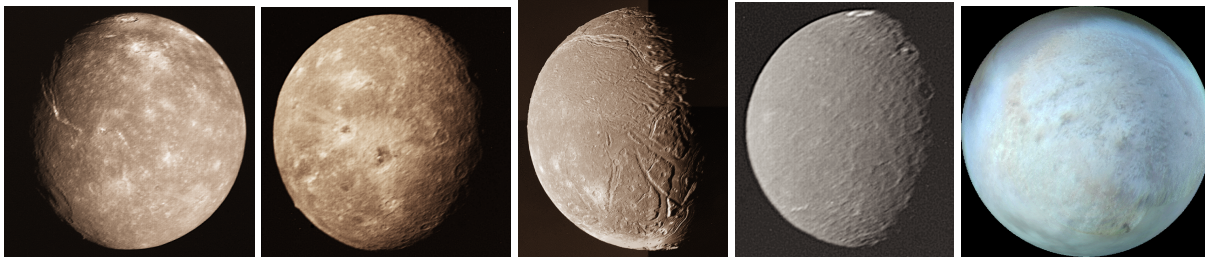


Figure 14-13. Largest moons of Uranus, (from left) Titania, Oberon, Ariel, & Umbriel, and Neptune's



Figure 14-14. *From left:* The asteroid Gaspra, comet Hale-Bopp, the nucleus of comet Borrelly, & the dwarf planet Eris with its Moon Dysnomia (image quality poor owing to faintness). [Source: nasa.gov]

## Summary

According to current scientific theory, planetary systems result naturally from the same general process that forms stars. A cloud of gas and dust collapses from gravity to create one or more stars at the center plus a disk centered on the star(s). Planets and smaller bodies assemble themselves from the material in the disk. This is aided by the slower orbits farther from the center, which allow larger solid chunks of matter, planetesimals, to gravitationally accrete “fresh” smaller ones that they continuously encounter. The wide range in temperature from the vicinity of the Sun to the outer disk caused differentiation, with mostly heavier atoms and molecules remaining at low orbits, lighter elements collecting farther out, and ices forming in the outer regions. This model explains an impressive array of observations: (1) the orbits of the planets all lie close to a single plane; (2) the orbits of all of the larger planets are nearly circular; (3) all of the planets and most of the moons revolve in a counterclockwise direction and most spin in a similar direction; (4) rocky objects are found close to the Sun, gas giants farther out, and icy objects at the greatest distances; (5) bodies fitting the description of leftover planetesimals remain in the form of icy comets and rocky asteroids; (6) stars with surrounding disks are observed; and (7) planets have been detected around many other stars (“exoplanets”), demonstrating that the process is not rare. The small number of odd spins, the origin of the Moon, and giant exoplanets found orbiting very close to their stars, can be explained by collisions or close encounters between planets and other massive bodies during the first few hundred million years after the Sun or star and planets formed.

The maintenance of an atmosphere is favored for planets and moons with substantial masses plus temperatures that are not too hot; for terrestrial planets, a source of gases from the interior (usually via volcanoes) can create a secondary atmosphere, as on the Earth. The Jovian gas giants still have their original atmospheres.

Newly formed terrestrial bodies were heated by their gravitational contraction, continued bombardment by leftover planetesimals, and decays of radioactive atomic nuclei trapped in their interiors. This melted the body, which caused condensations rich in heavy metals, especially relatively abundant iron and nickel atoms, to sink to the center to form a dense core. The silicon compounds and other rocky materials remained in a large layer called the mantle, while the outer crust cooled and solidified relatively quickly. This differentiation of a planet's interior provided the structure that we now find in the Earth and other terrestrial planets and moons.

The solar system today contains a large number of worlds that are rich and varied. On one of these planets — the Earth — life evolved. The next chapter will discuss the Earth in more detail, since it is our home and therefore we have explored it more thoroughly than we have other planets.

## Glossary

Gyr.: Gigayears, billions of years.

Radioactive dating: Determination of the age of material by the ratio of decay daughter products (lower mass isotopes) to parent radioactive atoms. See Chapter 8.

Differentiation: Process by which heavier elements and molecules in the disk, planets, and other bodies in a planetary system become prevalent closer to the star and lighter materials farther out. Or heavier atoms and compounds sink toward the center of a planet, moon, or asteroid to form the core while lighter material rises toward the outer part of the interior, forming the mantle.

Planetesimal: A body that has not yet become part of a planet. Usually in the form of a rock, small icy body, asteroid, or comet.

Accretion: Process by which bodies combine through the attractive force of gravity.

Angular Momentum: The equivalent of momentum for objects or particles that are spinning or moving along curved trajectories. For an object of mass  $m$  in a circular orbit of radius  $r$  at a speed  $v$ , the angular momentum is equal to  $mvr$ . Angular momentum is a conserved quantity.

Planet: A large body, orbiting a star, that does not produce its own visible light.

Moon: A natural satellite of a planet or dwarf planet. “The Moon” refers to the Earth’s moon.

Jovian (gas giant) planets: Objects, more massive than several times the Earth’s mass, with thick atmospheres throughout most of their volume. In our solar system: Jupiter, Saturn, Uranus, and Neptune.

Terrestrial planet: Object, less than several Earth masses (but more than about 1% of the Earth’s mass), composed mostly of rocky material. In our solar system, Mercury, Venus, the Earth, and Mars.

Center of mass: A mathematical point, defined by the values and placement of the masses of a system, that is the focus of the orbits of the bodies in the system. The center of mass of the solar system, in which the Sun and Jupiter contain most of the mass, is inside the Sun on a line between the Sun’s center and Jupiter’s center. The Sun’s center executes a tiny orbit about this point, causing the Sun to wobble.

Doppler shift: The change in wavelength (or frequency) caused by relative motion between the source of waves (e.g., light) and the observer. See equation (5-2).

Transit: Passage of a planet (or other opaque body) between the observer and a star (or other luminous body). This causes the brightness of the star to decrease during the transit. (This is the same as a partial eclipse.)

Habitable zone: The range of distances from a star where planets are likely to have temperatures (similar to the Earth's) that allow liquid water to be abundant.

Dwarf planet: A spherical body in orbit around the Sun whose mass is too low to maintain a nearly circular orbit or to clear out most of the planetesimals in its orbital path. The icy bodies Pluto, Eris, and Quaoar, plus the terrestrial body Ceres are four examples in our solar system.

Asteroid: A low mass, irregularly shaped solid body that orbits the Sun.

Meteor: A small solid body in space. Seen from Earth as a “shooting star” when it enters the atmosphere, becomes hot, and glows before burning out or landing on the ground. A meteor can either be a very small asteroid or a small chunk of a planet or moon expelled during a collision with an asteroid.

Meteorite: The remains of a large meteor that strikes the Earth or other body.

Comet: A small, mostly icy body. When a comet comes into the inner solar system, the Sun's heat vaporizes some of the ice, creating a spherical “coma.” The solar wind (particles streaming from the Sun) pushes on the coma to create a long tail of gas and dust that reflects sunlight.

Molten state: Liquid condition of rocky or metallic material when hot. (From word “melt”)

Core: The dense central region of a planet or moon.

Crust: The surface layer of a terrestrial planet, moon, or asteroid.

Mantle: A thick layer of rocky material in the interior of a planet or moon, between the core and crust.

Outgassing: Production of vapors from the interior of a solid body, usually via volcanoes.

Secondary atmosphere: Non-original atmosphere of a planet or moon, usually the result of outgassing.

Greenhouse effect: Trapping of heat by certain gases (*e.g.*, methane or carbon dioxide). Visible light passes through but infrared light radiated from the surface is absorbed. (This is the reason why a car left in the Sun becomes hot even on a cool day.)

## Questions for Discussion

- A. Could planets have formed if the young disk surrounding the Sun rotated as a rigid body rather than with orbital period decreasing with distance from the center of the disk?
- B. If the Sun's luminosity were highly variable ranging from 10% to 10 times its current luminosity, what effect would this have on the physical conditions of the planets? How about if the Sun had a companion star about 2 AU from it?
- C. Many of the massive planets discovered around other stars have highly elliptical orbits. How might the evolution of the planets have changed if Jupiter had an orbit with a closest approach to the Sun of 1 AU and a greatest distance from the Sun of 9 AU. What if Jupiter were several times more massive?
- D. How could a planet more massive than Jupiter have a highly elliptical orbit (as observed for a number of exoplanets) if the current model of the formation of planets is correct?
- E. Why have the searches for planets around other stars so far found mainly planets with masses much larger than that of the Earth?