Formation of the Solar System

Most of our knowledge of the formation of the Solar System has emerged from:

- studies of interstellar gas clouds,
- fallen meteorites,
- the Earth's Moon,
- the various planets observed with ground-based telescopes and planetary space probes.

Studies of Earth itself do not help much because information about our planet's early stages eroded away long ago. Meteorites and comets provide perhaps the most useful information, for nearly all have preserved within them traces of solid and gaseous matter from the earliest times.

As of early 2005, we know of more than hundred of **extrasolar planets**—planets orbiting stars other than the Sun. The other planetary systems discovered to date seem to have properties quite different from our own, and may well require us to rethink in some radical ways our concept of how stars and planets form. We currently have only the barest information on extrasolar planets — little more than orbits and mass estimates for the largest planets.

Basic properties of our Solar System as a whole may be summarized as follows:

1. Each planet is relatively isolated in space. The planets exist as independent bodies at progressively larger distances from the central Sun; they are not bunched together. In rough terms, each planet tends to be twice as far from the Sun as its next inward neighbor.
2. The orbits of the planets are nearly circular. In fact, with the exceptions of Mercury and Pluto, which we will argue are special cases, each planetary orbit closely describes a perfect circle.
4. The orbits of the planets all lie in nearly the same plane. The planes swept out by the planets' orbits are accurately aligned to within a few degrees. Again, Mercury and Pluto are slight exceptions.
5. The direction in which the planets orbit the Sun (counterclockwise as viewed from above Earth's North Pole) is the same as the direction in which the Sun rotates on its axis. Virtually all the large-scale motions in the Solar System (other than comet orbits) are in the same plane and in the same sense. The plane is that of the Sun's equator, and the sense is that of the Sun's rotation.
7. The direction in which most planets rotate on their axis is roughly the same as the direction in which the Sun rotates on its axis. This property is less general than the one just described for revolution, as three planets—Venus, Uranus, and Pluto—do not share it.
8. Most of the known moons revolve about their parent planets in the same direction that the planets rotate on their axes.
10. Our planetary system is highly differentiated. The inner terrestrial planets are characterized by high densities, moderate atmospheres, slow rotation rates, and few or no moons. By contrast, the jovian planets, farther from the Sun, have low densities, thick atmospheres, rapid rotation rates, and many moons.
11. The asteroids are very old and exhibit a range of properties not characteristic of either the inner or the outer planets or their moons. The asteroid belt shares, in rough terms, the bulk orbital properties of the planets. However, it appears to be made of primitive, unevolved material, and the meteorites that strike Earth are the oldest rocks known.
12. The comets are primitive, icy fragments that do not orbit in the ecliptic plane and reside primarily at large distances from the Sun.

One of the earliest heliocentric models of the Solar System formation is termed the **nebular theory**, and may be traced back to the seventeenth-century French philosopher René Descartes. In this model:

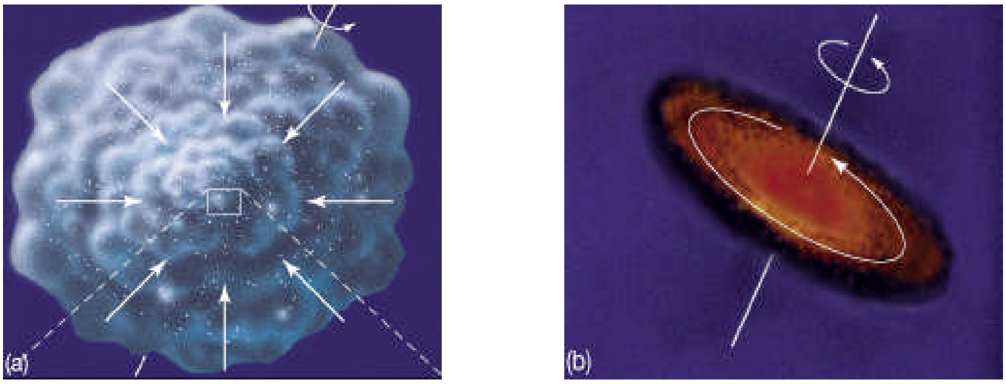
- A large cloud of interstellar gas began to collapse under the influence of its own gravity.
- As it contracted, it became denser and hotter, eventually forming a star—the Sun—at its center.
- While all this was going on the outer, cooler, parts of the cloud formed a giant swirling region of matter, creating the planets and their moons as by-products of the star-formation process.
- This swirling mass destined to become our Solar System is usually referred to as the **solar nebula**.

In 1796 the French mathematician-astronomer Pierre Simon de Laplace tried to develop the nebular model in a quantitative way. He was able to show mathematically that the conservation of angular momentum demands that an interstellar cloud like the hypothetical solar nebula must spin faster as it contracts. A decrease in the size of a rotating mass must be balanced by an increase in its rotational speed.

Nebular Contraction

(a)Conservation of angular momentum demands that a contracting, rotating cloud must spin faster as its size decreases.

(b)Eventually, the primitive Solar System came to resemble a giant pancake. The large blob at the center would ultimately become the Sun. Astronomers are fairly confident that the solar nebula formed such a disk because similar disks have been observed (or inferred) around other stars**.**



Laplace imagined that as the spinning solar nebula contracted, it left behind a series of concentric rings, each of which would eventually become a planet orbiting a central **protosun** — a hot ball of gas well on its way to becoming the Sun. Each ring then clumped into a **protoplanet**—a forerunner of a genuine planet.

The description of the collapse and flattening of the solar nebula is essentially correct, but when modern astronomers began to study the more subtle aspects of the problem, some fatal flaws were found in Laplace's nebular picture:

Calculations show that rings of the sort envisaged in Laplace's theory would probably not form, and even if they did, they would not in most cases condense to form a planet. In fact, computer calculations predict just the opposite: over most of the Solar System, the rings would tend to disperse.

The protoplanetary matter would be too warm, and no one ring would have enough mass to bind its own matter into a ball. Only in the cool outer regions of the nebula might it be possible for a sufficiently large clump of matter to form and survive.

The model currently favored by most astronomers is a more sophisticated version of the nebular theory. Known as the **condensation theory**, it combines the good features of the old nebular theory with new information about interstellar chemistry to avoid most of the old theory's problems.

The key new ingredient in the modern condensation theory is the presence of **interstellar dust** in the solar nebula.

Astronomers now recognize that the space between the stars is filled with microscopic dust grains (having typical sizes of about 10^{-5} m), an accumulation of the ejected matter of many long-dead stars. These dust particles probably formed in the cool atmospheres of old stars, then grew by accumulating more atoms and molecules from the interstellar gas within the Milky Way Galaxy.

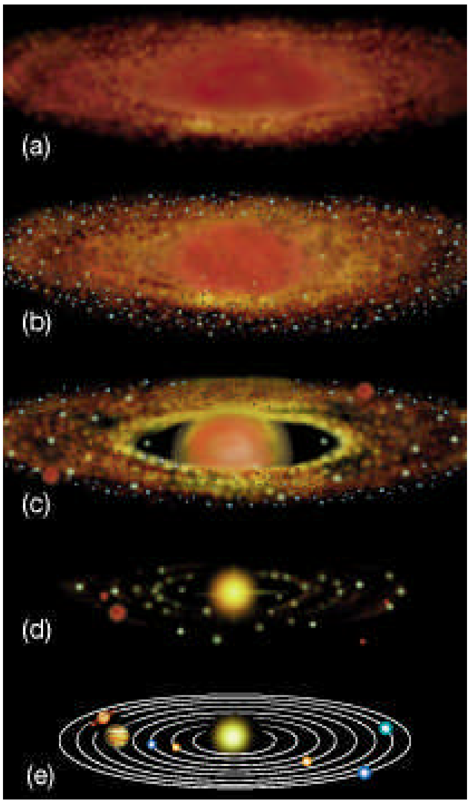
Dust grains play an important role in the evolution of any gas:

•Dust helps to cool warm matter by efficiently radiating its heat away in the form of infrared radiation, reducing the pressure (which is just proportional to the gas temperature) and allowing the gas to collapse more easily under the influence of gravity.

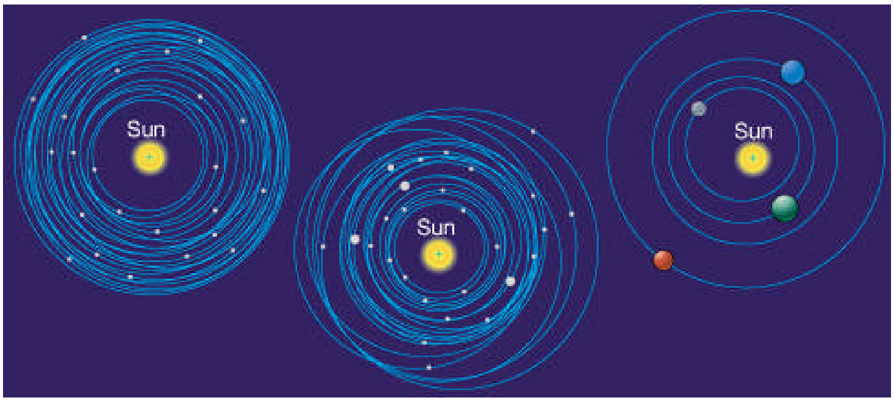
•The dust grains greatly speed up the process of collecting enough atoms to form a planet. They act as **condensation nuclei**—microscopic platforms to which other atoms can attach, forming larger and larger balls of matter.

The Solar System Formation Diagram:

(a)The condensation theory of planet formation (not drawn to scale; Pluto is not shown in part (e).
The solar nebula after it has contracted and flattened to form a spinning disk. The large blob in the center will become the Sun. Smaller blobs in the outer regions may become jovian planets.
(b)Dust grains act as condensation nuclei, forming clumps of matter that collide, stick together, and grow into moon-sized planetesimals. The composition of the grains depends on location within the nebula.
(c)Strong winds from the still-forming Sun will soon expel the nebular gas. By this time, some large planetesimals in the outer Solar System have already begun to accrete gas from the nebula.
(d)With the gas ejected, planetesimals continue to collide and grow. The gas giant planets are already formed.
(e)Over the course of a hundred million years or so, planetesimals are accreted or ejected, leaving a few large planets that travel in roughly circular orbits.



Accretion in the inner Solar System: Initially, many moon-sized planetesimals orbited the Sun. Over the course of a hundred million years or so, they gradually collided and coalesced, forming a few large planets in roughly circular orbits.



Formation of Jovian Planets: As an alternative to the growth of massive protoplanetary cores followed by accretion of nebular gas, it is possible that some or all of the giant planets formed directly via instabilities in the cool gas of the outer solar nebula.

As the primitive Solar System contracted under the influence of gravity, it heated up as it flattened into a disk. The density and temperature were greatest near the central protosun and much lower in the outlying regions. Detailed calculations indicate that the gas temperature near the core of the contracting system was several thousand kelvins. At a distance of 10 A.U., out where Saturn now resides, the temperature was only about 100 K.In the warmer regions of the cloud, dust grains broke apart into molecules, and they in turn split into excited atoms. Because the extent to which the dust was destroyed depended on the temperature, it also depended on location in the solar nebula. Most of the original dust in the inner Solar System disappeared at this stage, but the grains in the outermost parts probably remained largely intact.

Planetesimal Ejection: Ejection of planetesimals to form the Oort Cloud and Kuiper Belt. It is believed that interactions with Jupiter and Saturn "kicked" planetesimals out to very large radii (the Oort cloud). Interactions with Uranus and especially Neptune tended to populate the Kuiper belt but also deflected some planetesimals inward to interact with Jupiter and Saturn. As a result of the inward and outward "traffic," the orbits of all four giant planets were all significantly modified. Neptune was affected most, and may have migrated outward by as much as 10 A.U.

Cleaning up the Debris: All young stars apparently experience a highly active evolutionary stage known as the *T Tauri* phase, during which their radiation and stellar winds became very intense. It is thought that much of the nebular gas between the planets was blown away into interstellar space by the solar wind and the pressure exerted by the Sun's pressure when the Sun entered this phase, just before nuclear burning started at its center. The nebular disk was probably only a few million years old when this occurred. Afterward, all that remained were protoplanets, with the gas-rich giant planets already largely formed, and planetesimal fragments, ready to continue their long evolution into the Solar System we know today.

Overview of the Solar System

Our Solar System is known to contain

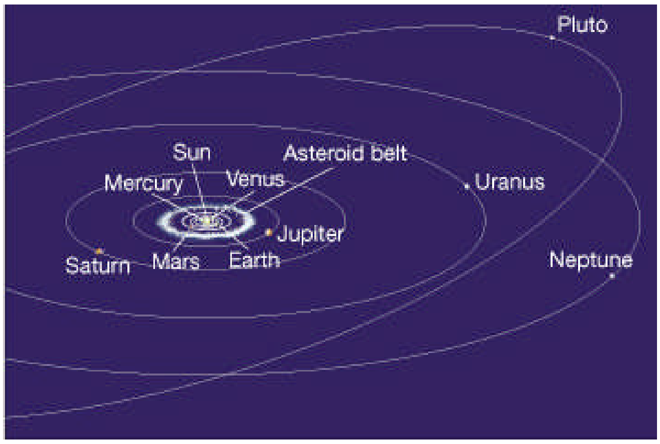
- one star (the Sun),
- nine planets,
- 91 moons (at last count) orbiting those planets,
- six asteroids larger than 300 km in diameter,
- tens of thousands of smaller (but well-studied) asteroids,
- myriad comets a few kilometers in diameter,
- and countless meteoroids less than 100 m across.

The list will grow as humans continue to explore our cosmic neighborhood.

The Sun, having more than 1000 times the mass of the next most massive object (the planet Jupiter), is clearly the dominant member of the solar system. In fact, the Sun contains about 99.9 percent of all solar system material. The planets—including our own—are insignificant in comparison. The distance from the Sun to Pluto is about 40 A.U., almost a million times Earth's radius and roughly 15,000 times the distance from Earth to the Moon. Despite the solar system's vast extent, the planets all lie very close to the Sun, astronomically speaking. Even the diameter of Pluto's orbit is less than 1/1000 of a light-year, whereas the next nearest star is several light-years distant.

The planet closest to the Sun is Mercury. Moving outward, we encounter in turn

- Mercury
- Venus
- Earth
- Mars
- Jupiter
- Saturn
- Uranus
- Neptune
- Pluto.



Planetary orbits are all ellipses, with the Sun at (or very near) one focus. Most planetary orbits have low eccentricities. The exceptions are the innermost and the outermost worlds, Mercury and Pluto. Accordingly, we can reasonably think of most planets' orbits as circles centered on the Sun.

Except for Mercury and Pluto, the orbits of the planets lie nearly in the same plane. As we move out from the Sun, the distance between the orbits of the planets increases. The entire solar system spans nearly 80 A.U.

•All the planets orbit the Sun counterclockwise as seen from above Earth's North Pole—and in nearly the same plane as Earth (that is, the ecliptic plane).
•Mercury and Pluto deviate somewhat from this rule. Their orbital planes lie at 7° and 17° to the ecliptic, respectively. We can think of the Solar System as being quite flat. Its "thickness" perpendicular to the plane of the ecliptic is less than 1/50 the diameter of Pluto's orbit.
•If we were to view the planets' orbits from a vantage point in the ecliptic plane about 50 A.U. from the Sun, only Pluto's orbit would be noticeably tilted.
•The planetary orbits are not evenly spaced: The orbits get farther and farther apart as we move farther out from the Sun.

On large scales, the Solar System presents us with a sense of orderly motion. The planets move nearly in a plane, on almost concentric (and nearly circular) elliptical paths, in the same direction around the Sun, at steadily increasing orbital intervals. However, the individual properties of the planets themselves are much less regular.
A clear distinction can be drawn between the inner and the outer members of our planetary system based on densities and other physical properties:
•The inner planets—Mercury, Venus, Earth, and Mars—are small, dense, and rocky in composition. The four terrestrial planets all lie within about 1.5 A.U. of the Sun. All are small and of relatively low mass, and all have generally rocky composition and solid surfaces.
•The outer planets—Jupiter, Saturn, Uranus, and Neptune (but not Pluto)—are large, of low density, and gaseous.

Because the physical and chemical properties of Mercury, Venus, and Mars are somewhat similar to Earth's, the four innermost planets are called the terrestrial planets. (The word *terrestrial* derives from the Latin word *terra*, meaning "land" or "earth.")
The larger outer planets—Jupiter, Saturn, Uranus, and Neptune—are all similar to one another chemically and physically (and very different from the terrestrial worlds). They are labeled the jovian planets, after Jupiter, the largest member of the group. (The word *jovian* comes from *Jove*, another name for the Roman god Jupiter.) The jovian worlds are all much larger than the terrestrial planets, and quite different from them in both composition and structure.

The terrestrial planets have density from about 3 to 5 g/cm^3. Typically they contain cores of iron and nickel surrounded by a mantle of dense rock.
•Mercury is only 40% larger than the Earth's Moon, and thus it has held no atmosphere. Its rocky surface is covered with thousands of craters.
•Venus is nearly as large as the Earth, and its atmosphere is thick with heavy clouds that hide its surface.
•The atmosphere on Mars is thin, and we can see its surface from space probes. Mars, about half the diameter of the Earth, is marked by impact craters and volcanoes.

The Jovian planets are rich in hydrogen and helium, so their average density is low ($<$ 1.75 g/cm^3).
All the Jovian planets are massive:
•Jupiter is over 318 times as massive as the Earth
•Saturn is about 95 Earth masses
•Uranus and Neptune are 15 and 17 Earth masses, respectively.
Photographs of the Jovian planets reveal swirling cloud patterns.

Differences between the terrestrial planets:

•All four terrestrial planets have atmospheres, but the atmospheres are about as dissimilar as we could imagine, ranging from a near-vacuum on Mercury to a hot, dense inferno on Venus.

•Earth alone has oxygen in its atmosphere and liquid water on its surface.

•Surface conditions on the four planets are quite distinct from one another, ranging from barren, heavily cratered terrain on Mercury to widespread volcanic activity on Venus.

•Earth and Mars spin at roughly the same rate—one rotation every 24 (Earth) hours—but Mercury and Venus both take months to rotate just once, and Venus rotates in the opposite sense from the others.

•Earth and Mars have moons, but Mercury and Venus do not.

•Earth and Mercury have measurable magnetic fields, of very different strengths, whereas Venus and Mars have none.

Beyond the outermost jovian planet, Neptune, lies one more small world, frozen and mysterious, - Pluto.

Pluto doesn't fit well into either planetary category. There is ongoing debate among planetary scientists as to whether it should be classified as a planet at all. In both mass and composition, it has much more in common with the icy jovian moons than with any terrestrial or jovian planet.

Many astronomers suspect that it may in fact be the largest member of a newly recognized class of solar system objects that reside beyond the jovian worlds. In 1999 the International Astronomical Union, which oversees the rules for classifications in astronomy, decided that Pluto should, for now at least, still be called a planet. However, that status may well change as the makeup of the outer solar system becomes better understood.

The Solar System is filled with three kinds of space debris: asteroids, comets, and meteoroids.

- Asteroids (minor planets) are small rocky worlds, most of which orbit the Sun in a belt between the orbits of Mars and Jupiter. Roughly 20,000 asteroids have been identified, of which about 500 to 1000 follow orbits that bring them into the inner solar system, where they can occasionally collide with a planet. About 200 asteroids are more than 100 km in diameter, and over 2000 are more than 10 km in diameter. There are probably 500,000 that are larger than 1 km.
- Comets are faint, and are difficult to locate even at their brightest. A comet may take months to sweep the inner solar system, during which time it appears as a glowing head with an extended tail of gas and dust. The nuclei of comets are icy bodies left over from the origin of the planets.
- Meteors are commonly called "shooting stars". They are a small bits of rock and metal falling into Earth's atmosphere and bursting into vapor about 80 km above the ground because of friction with the air. This vapor condenses to form dust, which settles slowly to Earth (about 40,000 tons per year). The word meteor refers to the streak of light in the sky. In the space, the object is called a meteoroid, and part of it that survives its fiery passage to Earth's surface is called a meteorite.

Asteroids and meteoroids are generally rocky in composition, somewhat like the outer layers of the terrestrial planets. The distinction between the two is simply a matter of size:

- anything larger than 100 m in diameter (corresponding to a mass of about 10,000 tons) is conventionally termed an asteroid;
- anything smaller is a meteoroid.

Many of these bodies are made of material that has evolved hardly at all since the early days of the Solar System.

Comets are quite distinct from the other small bodies in the Solar System.

- Comets are generally icy rather than rocky in composition (although they do contain some rocky material) and typically have diameters in the 1–10 km range.
- Comets are quite similar in chemical makeup to some of the icy moons of the outer planets.
- Comets represent truly ancient material (Even more so than the asteroids and meteoroids) — the vast majority have probably not changed in any significant way since their formation long ago along with the rest of the Solar System.
- Comets striking Earth's atmosphere do not reach the surface intact, so we do not have actual samples of cometary material. However, they do vaporize and emit radiation as their highly elongated orbits take them near the Sun.