Chapter/1

Formation of the Solar System

The formation and evolution of the Solar System, the planetary system that houses the Earth, is determined by a model now widely accepted and known as the «solar nebula hypothesis». This model was developed in the eighteenth century by Emanuel Swedenborg, Emmanuel Kant and Pierre-Simon de Laplace. Developments following this hypothesis have involved a wide variety of scientific disciplines including astronomy, physics, geology and planetology. Since the beginning of the conquest of space in the 1950s and following the discovery of exoplanets in the 1990s, models have been questioned and refined to take into account new observations. According to estimates from this model, the solar system began to exist 4.55 to 4.56 billion years ago with the gravitational collapse of a small part of a giant molecular cloud. Most of the mass of the initial cloud collapsed in the center of this area, forming the Sun, while its scattered remains formed the

protoplanetary disc on the basis of which the planets formed, moons, asteroids and other small bodies of the Solar System.
The Solar System has evolved considerably since its initial formation. Many moons were formed from the gaseous disc and dust surrounding their associated planets, while it is assumed that others were formed independently and then captured by a planet. Finally, others, like the Earth's natural satellite, the Moon, would (most likely) be the result of cataclysmic collisions. Collisions between bodies have occurred continuously to the present day and have played a central role in the evolution of the Solar System. The positions of the planets have slipped noticeably, and some planets have exchanged their places. It is planetary nebulae, and will leave behind a stellar corpse: a white dwarf. In the distant future, the gravitational attraction of stars passing in the neighborhood will then gradually tear the procession of planets of the old system away from its star. Some planets will be destroyed while others will be ejected into space. After several thousand billion years, it is likely that the Sun, having become a black dwarf, will be alone and frozen, without any gravitating body in

its orbit.

The history of the current theory

Pierre-Simon de Laplace, one of the founders of the solar nebula hypothesis.
The ideas relating to the origins and the future of the world are reported in the oldest known writings. Nevertheless, as the existence of the Solar System as it is currently defined was not yet known, the formation and evolution of the world did not refer to it. The first step that opened the door to a rational explanation was the acceptance of heliocentrism, which placed the Sun at the center of the system and the Earth in orbit around it. If this conception was known to the precursors, such as Aristarchus of Samos as early as 280 BC. J.-C., it remained in gestation for centuries, and it was widely accepted only at the end of the seventeenth century. The term "Solar System", strictly speaking, was first used in 1704. Immanuel Kant in 1755 and, independently, Pierre-Simon de Laplace in the eighteenth century were the first to formulate the hypothesis of the solar nebula. This hypothesis is the embryo of the standard theory

currently associated with the formation of the Solar System. The most important criticism of this hypothesis was its apparent inability to explain the relative lack of angular momentum of the Sun compared to the planets. However, since the early 1980s, the observation and study of young stars have shown that they are surrounded by cold disks of dust and gas, exactly as predicted by the solar nebula hypothesis, which earned him renewed credit. Determining what the future evolution of the Sun, the main actor in the Solar System, will be, requires understanding where it gets its energy from. Arthur Eddington's validation of Albert Einstein's principle of relativity teaches us that the Sun's energy comes from the nuclear fusion reactions taking place at its heart. In 1935, Eddington continued this reasoning and suggested that other elements could also have formed within the stars. Fred Hoyle elaborates on these bases and explains that evolved stars which are called red giants create a large number of elements heavier than hydrogen and helium within them. When a red giant finally ejects its outer layers, the elements that it has accumulated there are released and can be reintegrated into the formation of new star systems.

The current model of the formation of the planets of the Solar System, by accretion of planetesimals, was developed in the 1960s by the Russian astrophysicist Viktor Safronov.

Dating

Using radioactive dating, scientists estimate the age of the Solar System to be about 4.6 billion years old. Terrestrial zircon grains included in rocks newer than them have been dated to more than 4.2 billion years ago, or even up to 4.4. The oldest terrestrial rocks have an age of about 4 billion years. Rocks of this age are rare, because the Earth's crust is constantly being shaped by erosion, volcanism and plate tectonics. To estimate the age of the Solar System, scientists need to use meteorites that formed at the beginning of the condensation of the solar nebula. The oldest meteorites, such as the Diablo Canyon meteorite, are 4.6 billion years old; therefore, the Solar System must at least be that age. The condensation of the Solar System from the primitive nebula would have occurred in 10 million years at most.

Training

Pre-solar-Nebula

According to the hypothesis of the presolar nebula, the Solar System was formed as a result of the gravitational collapse of a fragment of a molecular cloud several light-years in diameter. Even a few decades ago, it was commonly believed that the Sun formed in a relatively isolated environment, but the study of ancient meteorites revealed traces of isotopes with a reduced half-life, such as iron 60, which is formed only during the explosion of massive short-lived stars. This reveals that one or more supernovas occurred in the vicinity of the Sun while it was forming. A shock wave resulting from a supernova could have triggered the formation of the Sun by creating denser regions within the cloud, to the point of initiating its collapse. Because only short-lived massive stars form supernovae, the Sun would have appeared in a wide region of massive star production, probably comparable to the Orion nebula. The study of the structure of the Kuiper Belt and the unexpected materials found there suggests that the Sun was formed among a set of stars grouped in a diameter of 6.5 to 19.5 light-years and representing a collective mass equivalent to 3,000 times that of the Sun. Different simulations of a young Sun, interacting with nearby stars during the first 100 million years of its life, produce abnormal orbits. Such orbits are observed in the outer Solar System, especially those of scattered objects.

One of these collapsing regions of gas, the "pre-solar nebula", would have formed what would become the Solar System. This region had a diameter between 7,000 and 20,000 astronomical units and a mass just greater than that of the Sun. Its composition was approximately the same as that of the current Sun. It included hydrogen, accompanied by helium and traces of lithium produced by primordial nucleosynthesis, forming about 98% of its mass. The remaining 2% of the mass represent the heavier elements, created by nucleosynthesis of older generations of stars. At the end of their lives, these ancient stars had expelled the heavier elements in the interstellar medium and in the solar nebula.

Because of the conservation of angular momentum, the nebula rotated faster as it collapsed. As the materials within the nebula condensed, the frequency of collisions of the atoms that composed them increased, converting their kinetic energy into heat. The center, where most of the mass was collected, became hotter and hotter, much more than the disk surrounding it. Over a period of 100,000 years, the competing forces of gravity, gas pressure, magnetic fields and rotation caused the contraction and flattening of the nebula into a rotating protoplanetary disk with a diameter of about 200 au and forming at its center a hot and dense protostar (a star within which hydrogen fusion cannot yet begin). At this point in its evolution, the Sun was probably a variable star of the T Tauri type. Studies of T Tauri stars show that they are often accompanied by disks of pre-planetary matter with masses of 0.001 to 0.1 solar mass. These disks extend over several hundred astronomical units — the Hubble Space Telescope has observed protoplanetary disks up to 1,000 au in diameter in star-forming regions such as the Orion nebula— and reach a temperature of a thousand kelvins at most.

After 50 million years, the temperature and pressure in the heart of the Sun became so high that its hydrogen began to merge, creating an internal energy source that opposed gravitational contraction until hydrostatic equilibrium was achieved. This marked the entry of the Sun into the first phase of its life, known as the main sequence. Main sequence stars get their energy from the fusion of Hydrogen into helium in their core. The Sun remains a main sequence star to this day.

Formation of planets

It is assumed that the various planets were formed on the basis of the solar nebula, a disc-shaped cloud, made of gas and dust, not having been directly engulfed in the formation of the Sun. The phenomenon, currently retained by the scientific community, according to which the planets were formed is called "accretion". According to this process, the planets are born from the dust grains of the accretion disk orbiting the central proto-star. As a result of direct contacts, these grains aggregate into blocks from 1 to 10 kilometers in diameter, which, in turn, collide with each other to form larger bodies about 5 km wide, planetesimals. The latter gradually increase as new collisions occur, increasing at the rate of a few centimeters per year for the next few million years

The inner Solar System, the region of the system within 4 au of the Sun, is too hot for volatile molecules such as water and methane to condense. Also, the planetesimals that form there can only consist of chemical components with a high level of sublimation, such as metals (such as iron, nickel and aluminum) and silicate rocks. These rocky bodies will become the terrestrial planets: Mercury, Venus, Earth and Mars. As these chemical compounds are quite rare in the Universe, corresponding to only 0.6% of the mass of the nebula, the terrestrial planets are not experiencing very significant growth11. The Earth's embryo grows in size by no more than 0.05 earth masses and ceases to accumulate matter 100,000 years after the formation of the Sun. New collisions and the fusion of bodies the size of quasi-planets then allow the terrestrial planets to grow to their current sizes (see Terrestrial Planets below).

When the terrestrial planets are formed, they continue to evolve in a disk of gas and dust. The gas is partially supported by the pressure mechanisms and therefore it does not orbit as fast as the planets around the Sun. The resistance induced by the medium causes a transfer of angular momentum and, as a result, the planets gradually migrate to new orbits. Mathematical models show that the temperature variations in the disk govern this migration speed, but the inner planets clearly tend to move closer to the Sun, as the disk dissipates. This migration finally places the terrestrial planets in their current orbits.

The giant gas planets, namely Jupiter, Saturn, Uranus and Neptune, form further outwards, beyond the ice line (also called the "frost line"). This line designates the limit, between the orbits of Mars and Jupiter, where the matter is cold enough for its volatile ice compounds to remain in the solid state. The ices that form the gas giants are more abundant than the metals and silicates that form the terrestrial planets. This allows the giants to become massive enough that they eventually capture hydrogen and helium, the lightest but also the most abundant elements in the Universe. The planetesimals formed beyond the ice line accumulate up to more than four earth masses over a period of three million years. Today, the four gas giants account for almost 99% of the total mass orbiting the Sun. Astrophysicists believe that it is no coincidence that Jupiter is located just beyond the ice line. The ice line would then accumulate large amounts of water by evaporation of falling ice from the outer regions. This would create a region of low pressure that would facilitate the acceleration of the particles orbiting at the border of this line and interrupt their movements towards the Sun. Indeed, the ice line acts as a barrier that causes the rapid accumulation of material about five astronomical units from the Sun. This excess material merges into a large embryo of about ten earth masses, which then begins to grow rapidly by engulfing the hydrogen present in the surrounding disk. The embryo then reaches 150 earth masses in just 1,000 years, until reaching its nominal mass, 318 times that of the Earth. The significantly smaller mass of Saturn could be explained by the fact that it would have formed a few million years after Jupiter, when there was less gas available in its environment.

Uranus and Neptune are supposed to have formed after Jupiter and Saturn. The powerful solar wind then blew away most of the disc's material. As a result, the planets have the opportunity to accumulate only a small amount of hydrogen and helium — no more than one earth mass each. Uranus and Neptune are sometimes called "failed cores", that is to say "failed cores". The central problem that the different theories of the formation of the Solar System encounter is associated with the time scale necessary for their formation. Where the planets are located, it would have taken them a hundred million years to aggregate their nuclei. This means that Uranus and Neptune probably formed closer to the Sun, near Saturn or maybe even between it and Jupiter, and that they later migrated outward (see "Planetary Migration" below). Not all movements in the planetesimal zone were necessarily directed towards the Sun ; the samples that the Stardust spacecraft brought back from Comet Wild suggest that the materials of the first formation of the Solar System migrated from the hottest regions of the system to the regions of the Kuiper Belt. After about four million years, all the gas and all the dust of the protoplanet disk are dissipated due to accretion on the Sun and the stellar winds of the young Sun. After this point, only the planetesimals remain.

Star cluster

According to simulations pre-published in August 2023, "the orbital distribution of scattered disk objects can be explained if a particularly close stellar encounter occurred from the beginning (for example, an M dwarf with a mass of ≃0.2 M appro approaching the Sun at ≃200 au). For such an encounter to occur with a reasonably high probability, the Sun must have formed in a stellar cluster with nT ≳ 104 Ma pc-3, where η is the stellar numerical density [i.e. the number of stars per unit volume] and T is the residence time of the Sun in the cluster ".

Further evolution

The first theories of the formation of the Solar System assumed that the planets formed in the vicinity of where they currently orbit. This point of view changed radically at the end of the twentieth century and at the beginning of the XXI century. Currently, it is believed that the Solar System was very different after its

initial formation from what it is today: several objects at least as massive as Mercury were present in the inner Solar System, the outer part of the system was much more compact than it is now, and the Kuiper Belt was much closer to the Sun.
At the beginning of the XXI century, it is commonly accepted within the scientific community that meteorite impacts occurred regularly, but relatively rarely, during the development and evolution of the Solar System. The formation of the Moon, like that of the Pluto-Charon system, is the result of a collision of Kuiper Belt objects. Other moons close to asteroids and other Kuiper Belt objects would also be the product of collisions. Such inter-shocks continue to occur, as illustrated by the collision of Comet shoemaker-Levy with Jupiter in July 1994, or the Tunguska event on June 30, 1908.

Terrestrial planets

At the end of the time when the planets were formed, the Solar System was populated by 50 to 100 moons, some of which were comparable in size to that of the protoplanet that would form Mars. The continuation of their growth was possible only because these organisms collided and merged with each other, under the effect of gravitation, for another 100 million years. One of these giant collisions is probably at the origin of the formation of the Moon, while another would have removed the outer shell of the young Mercury. This model cannot explain how the initial orbits of terrestrial protoplanets, which would have had to be highly eccentric to be able to collide, produced the remarkably stable quasi-circular orbits that terrestrial planets have today. One hypothesis for this "eccentricity dumping" is that the terrestrial planets would have formed in a disk of gas that would not have yet been expelled by the Sun. Over time, the "gravitational resistance" of this residual gas would have limited the energy of the planets, smoothing their orbits. Nevertheless, such a gas, if it had existed, would have prevented the Earth's orbits from becoming so eccentric at first. Another hypothesis is that the gravitational resistance took place not between the planets and the residual gases, but between the planets and the remaining small bodies. As the large bodies moved through a crowd of smaller objects, these, attracted by the gravity of the larger