ORIGIN OF THE SOLAR SYSTEM

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SPECULATION ABOUT the origin and evolution of the Earth and the celestial bodies is probably as old as human thinking. First it was speculation only, unaided by information. Then, with the advent of observation, experimentation and scientific reasoning, man has progressed a lot in solving the mystery.

But the problem of the origin of solar system poses enormous difficulty for the scientist deciding to probe it. The reason is that, astronomical observation can be made on thousands of stars, but we have only one solar system to observe. "A biologist who was able to examine only one sort of tree would find the study of evolution very difficult", says Dr. H. Reeves, a leading astrophysicist working on the problem [1].

This difficulty is more lucidly explained by Prof. William McCrea of University of Sussex : "It is, in fact, impossible to discover the origin of the solar system by observing it now, and working steadily backwards in time in order to infer the whole of its past history. This method cannot be applied to a strongly dissipative system, e.g., if we make every possible observation of the landing of a parachutist, we would be unable to infer anything of interest about the circumstances of his jump" [1].

This makes the steps in this investigation very much like those of a Sharlock Holmes, called in to discover the perpetrators of a crime. At first he searches for useful clues: ash, footprints etc.; then he reconstructs the crime with the help of those clues. These are his hypotheses. When the clues are insufficient, many different hypotheses would be able to account for the facts. As more clues are discovered, the detective zeros on to the criminal by rejecting the hypotheses that are inconsistent with the facts.

The history of the progress of man's understanding about the solar system has proceeded in about the same manner. Hence while trying to understand its origin, we will have to follow the historical course of events, proceeding clue by clue.

Before we go into the subject, it would be worth mentioning that true scientific investigation of the origin of the solar system could begin only after Newton. During the middle age, even asking this question was unthinkable because everything was thought to be created by God, the Supreme Creator. In astronomy, the Church-approved Ptolemic conception was that the Earth is fixed and all heavenly bodies including the sun revolve around it. When this geocentric conception crumbled in the sixteenth century owing to the work of Copernicus and Galileo, and Newton showed through his theory of universal gravitation that the movement of the stars and planets does not require any continuous application of force by a supernatural entity, the necessity of a God continuously moving these bodies began to be questioned. Having done away with the ageold mental roadblock (arising out of the belief that everything happens because God makes it happen), the scientists now turned their attention to the *origin* of it all. After all, if God did not play any role in planetary

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Box 1: BODE'S LAW

The so called Bode's law, ascribed to J. E. Bode (1747-1826), is not a physical law but only a convenient rule for recalling the distances of the planets from the sun. Write down a series of 4s, one for each planet. Add to the successive 4s the numbers 0 for Mercury, 3 for Venus, 6 for Earth, 12 for Mars, 24 for astroids, and so on. Insert a decimal point in each sum to divide by ten. The resultant series of numbers represents approximately the distances of the planets from the sun, in atronomical units (distance of Earth from the sun). Note that the Bode's law gives the distance to the asteroid belt and gives the distance of Pluto rather than Neptune.

	Merc.	Venus	Earth	Mars	Asteroid	Jupiter	Saturn	Urenus	Nept.	Pluto
Bode's Law	0.4+0 =0.4	0.4+0.3 =0.7	0.4+0.6 =1.0	0.4+1.2 =1.6	0.4+2.4 =2.8	0.4+4.8 =5.2	0.4+9.6 =10.0	0.4+19.2 =19.6	—	0.4+38.4 =38.8
Actual distance	0.39	0.72	1.00	1.52	≈2.7	5.2	9.54	19.18	30.0	39.6

motion, it is possible that He did not have any role in its creation also.

The initial 'clues'

Tycho Brahe, Kepler, and other astronomers of the renaissance era had noticed the outstanding "orderliness" of the solar system. The members of the solar system move in a common direction in elliptical orbits. The elliptical orbits for all the planets lie in almost the same plane. Thus, the solar system is practically 'flat'. Not only do the planets and thousands of asteroids follow this plane, but a great majority of satellites move about the planets in a similar fashion. Even Saturn's rings share in the common motion.

Next, there had come a new concept, very important in the study of planetary motion: the concept of *angular momentum*. The angular momentum of a planet is the product of its mass, speed and distance from the axis of rotation. As we know, a corrolary of Newton's laws is the law of conservation of angular momentum, that is, if no torque is applied by any external agency, the angular momentum of any body remains constant. This leads to the conclusion that the angular momentum of the solar system must have remained constant throughout the process of its formation.

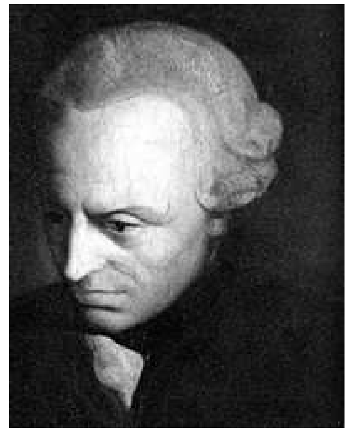
Moreover, since the speed diminishes only as the square root of the distance, a given mass contributes more angular momentum if it is placed at a greater distance from the sun. Jupiter, with its great mass, was found to carry about 60% of the entire angular momentum of the solar system. The four giant planets together contribute about 99%. The sun, with a thousand times the mass of Jupiter rotates so slowly that its angular momentum is only about 0.5% of the whole [2].

Lastly, it was found that the distance of the planets from the sun also exhibits some digree of coherence. The radius of each planetary orbit is roughly twice as large as that of the orbit nearest to it in the direction of the sun. The distances of the planetary orbits are given more accurately by the 'Bode law', which is explained in Box-1.

The Early Theories

When scientists started their attempt to formulate hypotheses, they had only the above clues to start with. The first initiative was taken in the year 1749 by the French naturalist George Buffon. He visioned a lonely sun a long time back, devoid of a planetary system. At some point of time, it had a collision with a comet that came from the depth of interstellar space. The impact tore a number of 'drops' from the sun, which went spinning about the sun due to the

George Louis Leclerc, comte de Buffon (1707-1788)



Emmanuel Kant (1724-1804)

gavitational attraction, and later condensed into planets.

A few years later, in 1755, an entirely different hypothesis was proposed by the famous German philosopher Immanuel Kant. He was the first to theorize that nothing in this world is static and unchangeable; everything is in a process of change or evolution. He was inclined to think that the sun made up its planetary system all by itself through a process of evolution without intervention of any other celestial body. Kant visualized the early state of the sun as a giant, cool mass of gas (a nebula), occupying the entire volume of the present planetary system, and rotating slowly around its axis. As the cloud condensed, the constancy of angular momentum would require it to increase the rotational speed. The increasing centrifugal force resulting from rapid rotation must have led to the progressive flattening of the gaseous body in the form of a disc. Secondary condensations formed in the disc and planets developed from these, whilst the primary condensation in the central region formed the sun (Figure 1).

The 'evolutionary' theory was later adopted and enriched by the famous French mathematician Laplace, who included a treatise on the subject in his book *"Exposition du Systeme du Monde"*, published in 1796. According to Laplace, the increase of rotational speed due to contraction of the nebular cloud would not only flatten it into a lens shape, but also eject a series of gaseous rings along its extended equator. These rings later condensed into planets circling at different distances around the sun (Figure 2). The theory has come to be known as Kant-Laplace hypothesis.

It is clear that the two theories paint two different pictures of the history of the solar system. As per Buffon, the sun existed

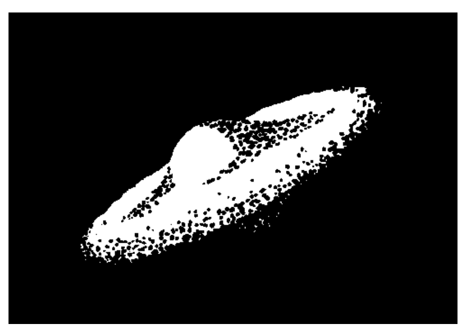


Figure 1: The disc-shaped solar nebula as per Kant's hypothesis.

Pierre Simon Laplace (1749-1827)

earlier and the planetary system came into existence later. As per Kant and Laplace, the whole of the solar system formed at the same time. Buffon's theory implies that the material that formed the planets was earlier inside the sun. Kant-Laplace theory implied that this material was never heated to solar temperature. These two theories gave birth to two schools of thought known as the catastrophic school and the evolutionary school.

Out of these two theories, the catastrophic theory of Buffon appeared to be a speculative hypothesis, not framed on the basis of the early clues like the unidirectional and coplanar rotation of the solar system. On the other hand, the Kant-Laplace theory did account for these observations. Hence, it sounded sensible and was popular in the first half of the 19th century.

However, when in 1860s, the English physicist James Clark Maxwell attempted to give a mathematical treatment to this theory, he found that if the material concentrated at present in various planets of the solar system was distributed uniformly through the entire space now occupied by it, the distribution of matter would have

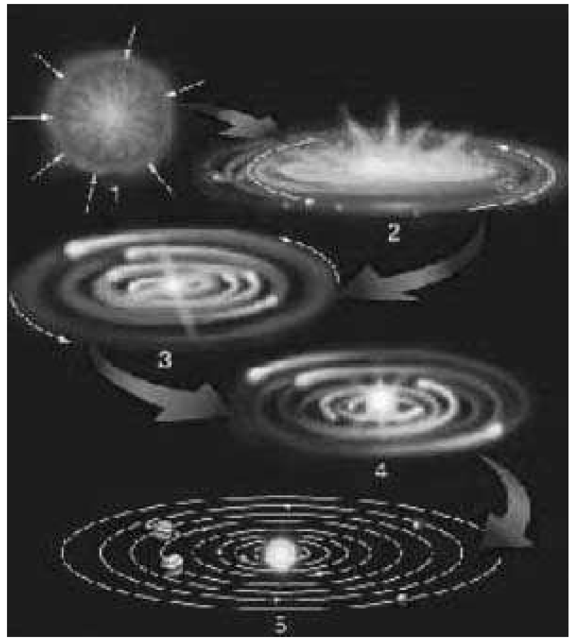


Figure 2: The evolution of the solar nebula as per Kant-Laplace theory.

been so thin that the forces of gravity would have been absolutely unable to collect it in separate planets. Thus in all likelihood, the gaseous rings would dissipate into surrounding space or at most form an astroidal belt. Moreover, how could 99% of the angular momentum be concentrated in the gaseous rings?

As a result, the nebular hypothesis of Kant and Laplace was virtually discarded and the catastrophic theory was brought back to life by the work of American scientists T. C. Chamberlin (1843-1928), F. R. Moulton (1872-1952) and the famous English scientists Sir James Jeans (1877-1946) and H. Jeffreys (1891-1989). By then another clue had surfaced: it was known that comets have so small a mass that a collision would have absolutely negligible impact on the sun. So Jeans and Jeffries modified the earlier theory by replacing the comet by a star which supposedly came very near to the sun. Its gravitational pull and the consequent tidal force tore away parts of the sun's body like a ribbon. As the star went away from the sun, the ribbon-like structure went spinning round the sun, and slowly condensed to form the planets (Figure 3).

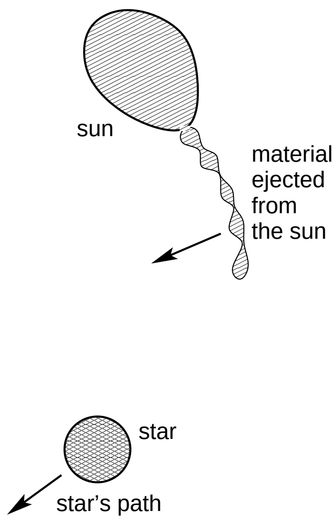
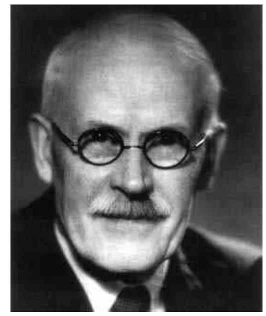


Figure 3: The Jeans-Jeffreys hypothesis.

However, the regenerated catastrophic theory, which seemed at that time to represent the only escape from the fundamental difficulties of the Kant-Laplace theory, was not found altogether satisfactory. It failed to explain why the hot gaseous fragments of the sun, thrown out either by direct collision or violent tidal action caused by another star passing close by, would condense to exhibit outstanding orderliness. The solar material is so hot that it is far more likely to dissipate than to condense into planets. However, with no other satisfactory answer to the questions being available, the scientists chose the lesser of two evils, and the catastrophic theory was accepted as the correct one, adopted until very recently in all scientific treatises, text books and popular literature. Even today, the school textbooks in our country teach the same theory as the origin of the solar system.



James Jeans (1877-1946)
and Harold Jeffreys (1891-1989)

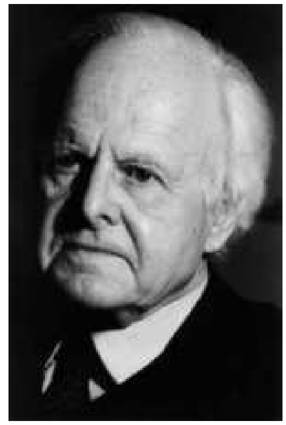
Next clue: The Chemical Composition of the Sun and the Planets

It was believed at that time that the sun and the planets were constituted by the same chemical elements in the same proportion; one is only the cooled and condensed state of the other. Geochemical analysis revealed that the body of the earth is made chiefly of iron, silicon, oxygen (in the form of various oxides) and smaller quantities of other heavy elements. Light gases such as hydrogen and helium are present on the earth only in very small quantities compared to the other elements. In the 1920s and 1930s, through elaborate spectroscopic analysis, scientists came to the striking conclusion that the chemical elements that form the body of the earth constitute only about 1% of the mass of the sun, the rest being almost evenly distributed between hydrogen and helium. Most of the other stars were found to have the same composition. Further, it was found that the interstellar space is not quite empty; it is filled by a mixture of gas and fine dust with a mean density of about 1 mg in 1,000,000 cubic miles of space, and this diffuse, highly rarefied material apparently has the same chemical composition as the sun and the other stars. The striking difference in chemical composition of the sun and the planets implies that the planets could not have formed through direct cooling and condensation of the material of the sun.

Resurrection of the evolutionary theory

In 1944, the German scientist Weizsácker showed that the above observation fits directly into the scheme of the evolutionary hypothesis. According to him, there is no reason to believe that the original mass of the solar nebula has remained unchanged as the solar system formed. He proposed that the primordial gaseous envelope of the sun was originally formed from such interstellar material and had a mass at least 100 times the present mass of the solar system. Hence the force due to gravity was sufficient to condense the central mass to form the sun. The planets formed only out of the minute amount of dust particles and other condensable material through mutual collision in the gaseous envelope. The rest of the light gases later dispersed into the surrounding space. Weizsácker developed elaborate mathematical model of his theory and showed that progressive accumulation of dust particles had a maximum probability of occurring only at certain distances from the sun, where the planets exist today.

Weizsácker's theory made it easy to see how the planets would form, eliminating the difficulty of trying to imagine how gaseous rings could coalesce into planets. Moreover, it was the only theory that could account for all the clues, even the one regarding the distances between the planetary orbits. However, this theory had only one shortcoming. Although Weizsácker described a mechanism by which angular momentum could be transferred from the sun to the forming planets by means of turbulence in the nebular cloud, later mathematical calculations showed that this mechanism alone could not result in the slow stately rotation of the sun. Thus Weizsácker's work could not be taken as revealing the entire truth. However, the historical importance of his work was that it brought the evolutionary theory again into limelight.



Carl Friedrich von Weizsäcker (1912-2007)

Some researchers tried to take other factors into consideration (like the effect of sun's magnetic field) to make up the deficiencies of the above theory. Though most of the scientists were convinced that Weizsácker's work was a step in the right direction, there were some who tried to devise entirely different models to fit into the clues. The clues unearthed till then did support one theory, but did not eliminate the others.

The other theories

In this situation, it is natural for scientists to propose more hypotheses which are not negated by the observed facts. Thus, many theories were tabled, which we will broadly classify into four groups for the sake of convenience. The groups are defined by the response of each theory to the following two questions:

1. Were the sun and the planets formed at the same time, in other words, are they co-genetic?

2. Were the planets formed from interstellar material or from stellar material (i.e., material that was part of a star)?

The first group, of course, was the Kant-Laplace theory enriched by the work of Weizsácker. Scientists like Kuiper, Levin, Hoyle, McCrea, Schatzman, and Cameron contributed to this line of work.

The second group of models similarly requires the formation of planets from a cloud of interstellar material but suppose that cloud had been captured by the previously formed sun. Hoyle and Lyttleton, and Schmidt independently proposed the following sequence: At some stage the sun passed through one of the many dense clouds which occur throughout the galaxy. Having a gravitational field, the sun captured a portion of this gas, which consequently encircled the sun forming a nebula similar to that supposed by Laplace. This group also includes the hypothesis of Alfvén and Arrhenius, who suppose that the magnetic field of an isolated sun trapped ionised material from interstellar space which slowly kept on accumulating to form the planets. Their theory does not require a massive cloud but a gradual addition of interstellar material.

The third group of models (e.g., that proposed by Lyttleton) supposes that the sun, at formation, was associated with a close twin sister with which it formed a double star. This sister star, due to some reason, disintegrated and a portion of its gaseous mass was captured by the sun and formed a cloud similar to that discussed in the previous theories.

The fourth group advocated the theory of stellar collision discussed earlier, which was supported by Jeans and Jeffreys early in this century, and later in a somewhat modified form by Woolfson. Woolfson conceived the assaulting body as a proto-star in the pre-ignition stage, which makes the planets form from material that never took part in thermonuclear reaction.

Research in this line was in a mess for three decades with so many conflicting theories claiming to account for much of the facts. Facing such a situation, the scientists started looking for fresh clues in a "directed" way—clues that would help in eliminating some theories. The textbooks continued to carry the old catastrophic version of planetary evolution.

The clinching evidence

The next clue surfaced in the early seventies when scientists acquired the ability to measure accurately the proportion of various isotopes (atoms with the same number of protons but different number of neutrons in the nuclei, for example hydrogen and deuterium) of elements present in a certain sample. It was found that on the earth, in other planets, and in interstellar gas, the deuterium to hydrogen ratio is about 2×10^{-5}. Deuterium is rare, but extremely stable unless subjected to great heat, as inside the stars. The measured D/H ratio in the sun's atmosphere is only about 3×10^{-7}. This observation immediately leads to the conclusion that the material forming the body of the planets was never the part of sun or another star. If it was, the D/H ratio would have been the same as in the sun. This clue thus eliminated the theories that made the planetary system out of gases ejected from the sun, from passing stars, or from collision of stars.

Having eliminated the sun and stars as the sources of our planetary material, the scientists had to address the question whether the sun and the planetary system developed around the sun out of 'captured' interstellar material. If the age of the planets and the sun could be measured accurately, the question would be answered.

We know that the age of a piece of rock can be determined by measuring the extent of decay of radioactive materials. By this method it has been found that the earth, the other planets and the meteorites formed within a relatively short period around 4.6 billion (4.6×10^9) years ago. But alas, we cannot measure the age of the sun with that accuracy.

We have another clue, however: the measured ratio of abundant carbon of atomic weight 12 to rare carbon of weight 13. This ratio varies quite greatly among stars and interstellar clouds, but is unaltered at stellar temperatures. Hence, if the ratio is the same for the whole of the solar system, it would be definitely co-genetic. The measured values do conform to this fact, but some scientists feel that the accuracy achieved to date is too poor for a definite conclusion [2].

Even though the rough constancy of the $^{12}C/^{13}C$ ratio is only indicative and not definitive, most investigators now favour the cogenetic origin of the sun and the solar system. They find that it would be very difficult for the isolated sun to capture an adequate amount of interstellar gas and dust. The solar wind (the continuous stream of high velocity particles coming out of the sun) is effective in blowing away the gas while the direct radiation prevents the fine interstellar dust from collecting on or near the sun. "In moving through interstellar clouds, even relatively dense ones, the sun by itself would maintain a clear volume near it and would simply plow through the interstellar cloud," argues Prof. Fred Whipple of the Harvard University [2]. Thus a star is more likely to drive away interstellar matter from it than collect it by gravity.

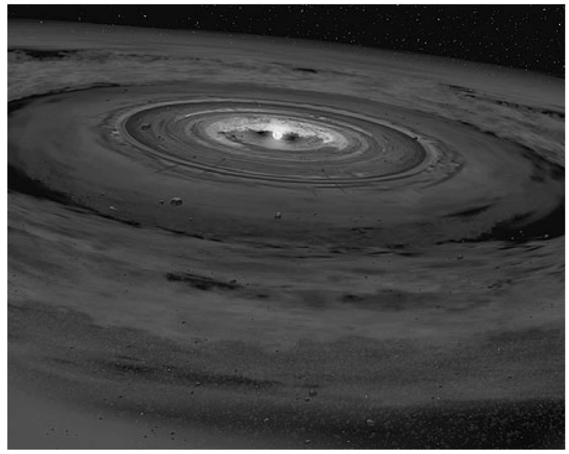


Figure 4: Artist's impression of the early solar nebula from which the planets formed.

The presently accepted theory

Having understood *how* scientists reached the conclusion that the whole solar system—comprising the sun, the planets, the asteroids, and the comets—came into existence through the evolution of a single nebula, let us now present the picture of how the solar system evolved.

It all started from a great interstellar gas-and-dust cloud, or a nebula. Hydrogen and helium formed much of its material, while the other heavier elements constituted only about 1% of its mass. At low temperature the volatile compounds like water, ammonia, carbon dioxide, methane etc. were in solid form. We will call them 'ices'. There were iron and silicates in the form of small solid grains. We will call them 'dust'. The whole gas-ice-and-dust cloud was rotating slowly about an axis.

At some point the nebula began to condense under its own gravity—a process called "gravitational collapse"—which most probably was triggered by a nearby supernova. Since angular momentum cannot change, as the nebula condensed its rotational speed increased. This caused the nebula to take the shape of a flattened disc. More mass accumulated near the centre and a compressed central part developed, which is termed as the proto-sun. Till the pressure at the centre reached a value sufficient to start thermonuclear reaction, the gas cloud was cold.

In the dusty envelope of the solar nebula, the silicate and metal particles coalesced first to form larger grains. Silicate molecules and metal atoms cling together tightly, thanks to electromagnetic forces among their electrons, so that they do not depend on gravitation to hold them together. As the grains grow, both by sticky encounters and by condensation of ices from the gas, the grains fell to the equatorial plane of the nebula due to the interaction of gravitational and centrifugal forces (Figure 4). Through collision of particles in that equatorial plane, sizable bodies began to grow, which later would *attract* more particles and gas once they grew to have considerable gravity (the "snowball effect"). These bodies are called protoplanets, which contained a rocky interior, the ices, and held a considerable amount of hydrogen and helium by gravity forming their primordial atmosphere. Since the flattened disc has a natural tendency to break up into rings, the probability of the formation of the planets was maximum at specific distances from the sun.

At the same time another process was going on. The magnetic field due to the fast rotating proto-sun stretched upto the surrounding gaseous envelope and got linked with it. By means of these magnetic lines of force, the angular momentum of the protosun was slowly transferred to the rotating envelope which began to rotate faster and the sun slowed down. The mechanism is explained in Box-2.

As the planets grew in size, the heat generated by the decay of radioactive elements heated their interiors. However, as their substance did not conduct heat well, the surface remained cold and the gases did not dissipate at this stage.

Perhaps the planets had already completed the preliminary process of formation when the condensing sun reached nuclear ignition and blazed out. When that happened, two new factors were introduced.

First, the sun started emiting radiation that heated the surface of the newly formed planets. Second, the sun started emiting streams of charged particles (solar wind) in all directions. During the birth of a star the stellar wind is very intense as we see in the stars which are forming now. This solar 'gale' slowly blew off the great mass of light gases from the surrounding nebula leaving the planets exposed. Thus, at this stage, the planets came out of the solar nebula and started their individual process of evolution.

The warming of the planetary surface increased the dissipative tendency, so that clouds of hydrogen/helium vapour would rise from the planets. The solar wind would then sweep the vapour away from the planets.

Three important factors determine which molecules can escape and which are trapped by the atmosphere. The heavier the planet, i.e., the stronger the gravitational field, the harder it is for the molecules to escape. The colder the atmosphere, the slower the average motion of molecules and hence, the harder for the gases to escape from the atmosphere. Finally, the heavier the molecules, the more strongly they are held back by the gravitational field. Hence, light molecules escape more easily than heavy ones.

The planets that formed nearest the sun would have the greatest tendency to vapourize and would be strongly subject to the sweeping-away effect of the solar wind. Those nearby planets would therefore decrease in mass. As they did so, their grav-

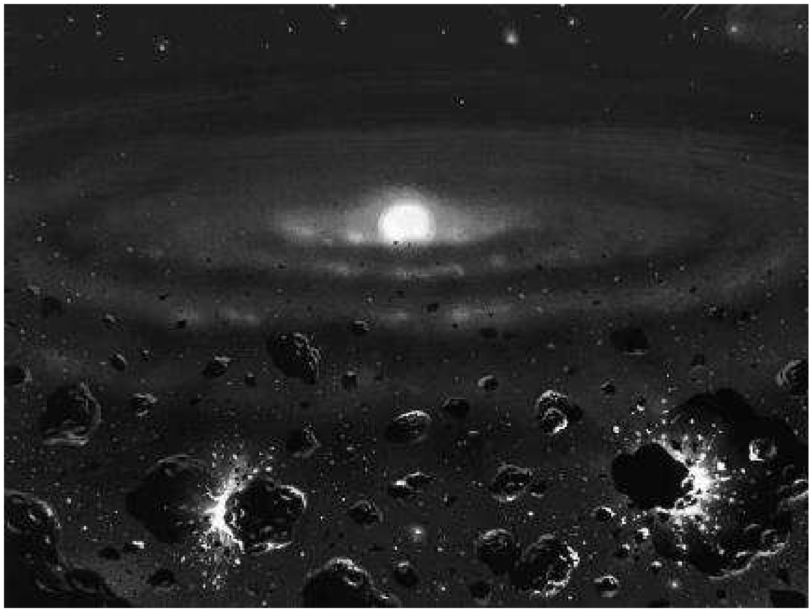


Figure 5: Artist's impression of the formation of the planets through collision and accretion.

itational fields would decrease in intensity, and both vapourization and sweeping-away would accelerate. In this way, the Mercury lost all its atmosphere and is now a mass of hot rock. The 'terrestrial' planets like the Venus, Earth and Mars lost all of the hydrogen and helium and most of the other volatile matter. They, however, retained some of the heavier molecules like N_2, H_2O, CO_2, NH_3, CH_4 etc. The Earth, "fortunately", was so placed that it retained the right amount of constituents in the right proportion so that life could originate here.

On the other hand, The distant planets like Jupiter and Saturn were large and cold enough to retain all the substances in their atmosphere, including hydrogen and helium (hence the name 'gas giants'). They have small rocky core and very thick atmospheres composed mainly of hydrogen and helium. Uranus and Neptune also contain mainly hydrogen and helium with small quantities of the heavier elements.

The comets were formed at the outer fringes of the nebula and are composed entirely of dust and ice particles. They did not hold the lighter gases because of their small mass. Pluto is also assumed to be of predominantly cometary composition, and is no longer considered to be a full-fledged planet.

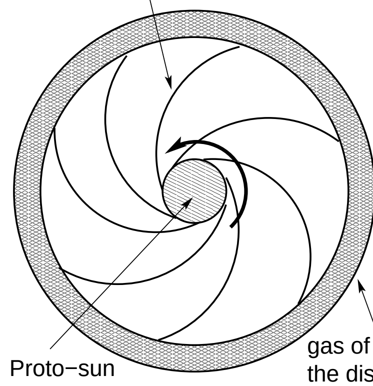
After the solar wind blew off the great mass of hydrogen and helium (about 100 times the present mass of the solar system), the transfer of angular momentum by magnetic field coupling could no longer continue. However, the sun's rotation continued to slow down as the solar wind removed the kinetic energy and caused a 'magneto-hydrodynamic braking'.

Continuing in this process, the sun settled to its present size and brightness, and the planetary system settled to the state as we see now.

Box-2

Transfer of angular momentum through magnetic field [3]

According to a theory proposed by Sir Fred Hoyle, the situation in the protosolar nebula can be aptly represented by the following analogy. Suppose the contracting star is represented by the hub of a bicycle wheel as shown in the figure. The material in the outer reaches of the disc is represented by the rim. The spokes of the wheel are the lines of force buried in the star at one end and the surrounding material at the other. To make the analogy complete, we suppose that the spokes are not made of steel, but of elastic material. If we rotate the hub of such a wheel very rapidly, it is easy to see that the kinetic energy will be transferred to the rim via the elastic spokes. Similarly, the rotation of the contracting proto-sun was transferred to the surrounding material via the lines of magnetic force, setting it to spin faster.



Conclusion

From the above account it is clear that there is no longer any need to take recourse to imagination in describing how the sun, the Earth and the other planets originated. Science has now provided an account of the process that has been obtained through the formation and testing of hypotheses. It is now known that the solar system originated from a diffuse gaseous nebula in a process of evolution.

It can also be seen that the evolutionary process did not proceed in a continuous and uniform pace. At times it has been slow, at times fast. At one time the contradiction between the gravitational and centrifugal forces in the nebula is of utmost importance; at another time the contradiction between the mutual repulsion of the hydrogen nuclei and their tendency to fuse under pressure acquires prime importance; at yet another time the contradiction between the gravitational snowballing of the planets and their dissipative tendency becomes the most important phenomenon in the process. And there have been major breaks or turning points in the evolutionary history of the solar system.

As of now, it has been conclusively established that everything, starting from the microscopic organism to the whole universe, is continuously changing—in a continuous process of evolution. The evolution of the solar system gives us a view of the general evolutionary process and help us in dispelling the mythological beliefs about the origin of our earthly abode. □

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