

Chapter 2

The Solar System

Abstract A very brief overview is presented of current conceptions about the state of the interstellar medium, interstellar clouds, and the role of the supernova in their evolution. The main information available on the physical parameters of the Solar system is presented and there is a discussion of the modern conceptions about the processes that brought about the formation and evolution of the Solar system.

Keywords Interstellar medium • Supernovas • Formation of the solar system • Role of short-living radioactive isotopes

2.1 Interstellar Clouds

Any model which attempts to describe the process of formation of the planetary systems must proceed from the definite initial condition of the material state from which the stars and the planetary systems were formed. At the present time, it is assumed that such state coincides with the state of the interstellar gas–dust clouds [1]. The following data, according to [2], are the basis of that assumption:

1—Young stars exist in surroundings of gaseous and gas-dust clouds. Many of them have massive optically dense disks with diameters from 10 to 1000 AU and a life time from 1 to 10 million years; 2—at least 4 % of the main part of the stars has planetary systems. The masses in these systems have values from 1 to 10 Jupiter masses and orbital radii from 0.05 to 5 AU. Below, we give a brief data overview of the sizes, composition and particles concentration in the interstellar clouds and the possible transformation mechanisms of scattered cloud matter into stars. The main characteristics of molecular clouds and the interstellar medium surrounding them are presented in Table 2.1.

The density of the matter in the core of molecular clouds is 10^3 – 10^5 molecules/cm³ [4]. 50 different molecules are detected in the gaseous phase of the molecular clouds. These are mainly hydrogen, H₂O, CO and relatively small molecules of organic compounds up to ethanol: C₂H₅OH. About 10 % of the Galaxy mass is concentrated

Table 2.1 The main dynamical characteristics of the interstellar media [3]

Phase	Indicator	Temperature (K)	Concentration/cm ³	mass %	Volume %
Molecular clouds	CO, OH	10–60	10 ⁻² –10 ⁻⁷	40	1/2
Clouds HI	λ 21 cm	50–100	1–50	40	5
Intercloud media	λ 21 cm	7000	0.2	20	40
Clouds H II	Hα, OIII	10 ⁴	10 ⁻² –10 ⁻³	Low	Low
Coronal gas	O VI	10 ⁻⁵ –10 ⁻⁶	10 ⁻³ –10 ⁻⁴	0.1	50

in the molecular interstellar clouds [5]. Besides the gaseous phase, the interstellar clouds contain dust particles with sizes around 0.1 μ, the composition of which is not defined, and their masses part is equal to 1 %.

According to Evans, the molecular clouds can be divided into two groups. In group A, Evans classifies clouds in which the temperature is lower than 20 K, and in group B are clouds, in some areas of which the temperature is higher than 20 K [1]. The physical conditions in clouds A and B are presented in Table 2.2.

It is presumed that stars are formed in the cores of massive clouds or in the whole volume of small clouds. Evans distinguished three stages of the evolution of massive cloud cores [1].

1. At low temperature and high density the cloud begins to compress. The cloud density increases, but the temperature remains low at this stage. With growing density, the number of collisions with dust particles also grows and the kinetic temperature becomes linked with the dust temperature.
2. If at the first stage a massive proto-star occurs, it will heat the remaining matter in the core dust.
3. The third stage passes with high temperature and low densities. At this stage, this can occur only through the formation of a very massive star, when an area with low density but high temperature forms [1]. From this it is inferred that if the initial material from which stars and planets form is molecular clouds, the material must necessarily evolve through a high temperature gas condition.

Table 2.2 Physical characteristics of molecular clouds [1]

Characteristic	Group A		Group B	
	Envelope	Core	Envelope	Core
T K	10	10	10–20	20–70
ncm ⁻³	10 ² –10 ³	10 ⁴	10 ³ ?	10 ⁵ –10 ⁶
M/Mo	20–?	?	10 ³ –10 ⁵	10 ² –10 ³
MJ/MO	8–24	2	?	2–4
Strong IR radiation	No	No	No	Yes
n(HCO+)/n	?	2 × 10 ⁻⁹	?	2 × 10 ⁻¹¹

2.2 The Role of the Supernova in the Formation of the Solar System

The role of the supernova in the formation of planet systems of the solar type is determined by two factors. The supernova explosion, which is accompanied by the ejection of a tremendous mass of material, can be a trigger mechanism for collapse of the molecular cloud. Furthermore, the molecular cloud, from which a system like the Solar system could be formed as a result, must contain short-living isotopes and heavy elements, which are absent in the molecular clouds and which could be formed only by the supernova explosion [6]. Therefore, the question about the source of these elements and the process of their formation is very significant for any model of the formation of the Solar system.

Herbst and Assusa [5] and Shramm [6], as the main proof of supernova participation in the formation of a solar type system, indicated the presence in the Solar system of an anomalous concentration of ^{26}Mg , which was formed by the decay of the short-living isotope ^{26}Al . In [6], the following scenario was suggested. According to Shramm [6], the universe existed and evolved for 7–15 billion years before the processes began that lead to the formation of the Solar system. It is assumed that the interstellar material contained gas and dust and heavy elements entered into the dust composition, which had been formed earlier by supernova explosions. The Galactic spiral wave passed through the cloud every 10^9 years, stimulating the formation of stars. One or more massive stars were formed when this wave passed through the gas and dust, then, in the vicinity of the present Solar system, one or some stars were formed in the cloud, and quickly evolved and exploded. The ejected material had a composition that was specific to the r-process. It is possible that this material was ejected in the form of jets [6]. The next spiral wave, which passed through the gas-dust cloud 4.6 billion years ago, again initiated the formation of stars, which were introduced during the evolution process into the proto-solar cloud ^{26}Al together with ^{16}O and other anomalous infusible elements. It is important to note that ^{26}Al could not be present in any clouds whose age was more than 10 million years.

The physical characteristics of the matter which had been ejected by the explosion of the supernova will differ significantly from the initial material of the molecular cloud. Firstly, the concentration of particles from that release could be higher than in the molecular cloud, and secondly the ejected material will have an initial temperature such that it will be in the gaseous state and, during its cooling, equilibrium condensation of the solid phases could be possible.

The works of [7] are devoted to the problems of the sources from which the short-living isotopes were introduced into the Solar system. In the works of Ouellette et al. two models are considered: the trigger model and aero gel model. The trigger model assumes that the explosion of the supernova was the mechanism that triggered the collapse of the molecular cloud, into the core of which the short-living isotopes were introduced. This model provides the development of the process, according to the second scenario, which is discussed in the work of Herbst [5]. The trigger model has

been considered in more detail by Boss [4]. It is evident that this model makes sense only if, after the enrichment of the molecular cloud by short-living isotopes and heavy elements, the sun, as a star of small dimensions, and around the Sun a proto-planetary disk, could be formed. In that case, the interval between the supernova explosion and the solid fragments of CAI occurring, enriched by ^{26}Al and Ca, must be no more than 1 million years [4].

The aero gel model is based on the assumption that the Sun is a star that has a small mass, formed in the direct vicinity of the massive stars cluster [4]. It is suggested that the population of stars existed at a distance of less than 2000 AU from the Sun and that 70–90 % of the proto-stars were formed in that cluster [8]. The short-living isotopes were synthesized into the supernova from that cluster and injected into the proto-sun cloud as dust particles. Williams and Gaidos [9] and Gounelle and Meibom [10] showed that the possibility of the injection of these elements in the 1 million years after a supernova explosion is less than 1 %. Nevertheless, Ouellette et al. consider that this possibility is enough to explain the origin of short-living isotopes and especially ^{60}Fe in the Solar system [7], with the use of the aero gel model. From that, the question arises: for what reason was it necessary to inject short-living isotopes into the proto-Sun cloud from the outside, if we can assume that the proto-Sun cloud itself represents material that could be ejected by the supernova? It seems that the delivery of these elements from the different sources assumed in different models does not solve this problem, because besides the short-living isotopes of aluminum, manganese and elements of the iron group in the Solar system, heavy elements also exist, which could occur only after a supernova explosion.

A significant factor that defines the possibility of the Solar system forming from the material ejected by the supernova explosion is the distribution of short-living isotopes in the volume of the proto-sun cloud. It is evident that, if that assumption is right, the distribution of ^{26}Al in the proto-sun cloud must be uniform and the value of the ratio of $^{26}\text{Al}/^{27}\text{Al}$ must be near to the value 5×10^{-5} [11].

The basis of the conclusion about the heterogeneous ^{26}Al distribution in the proto-sun cloud are the values of the ratio of $^{26}\text{Al}/^{27}\text{Al}$, obtained for the fragments of CAI enriched by Ca, and Al inclusions in carbonaceous chondrites, as presented in [12].

But these data [11] do not provide a unique conclusion about the heterogenic distribution of ^{26}Al in the proto-solar cloud. The value of the $^{26}\text{Al}/^{27}\text{Al}$ ratio can differ from the canonic one, which is 5×10^{-5} , for two reasons. Firstly, condensation of the corundum and other elements enriched by Al that enter the composition of CAI occurs over 1–3 million years and the later the condensed mineral was formed, the less would be the ratio in it of $^{26}\text{Al}/^{27}\text{Al}$. Secondly, corundum and gibbonite, for which ratios are measured, are often associated with spinel, and part of the ^{26}Mg can move to spinel from these minerals by diffusion. This is in agreement with the finding that the ratio of $^{26}\text{Al}/^{27}\text{Al}$ with the minimum values can be obtained by analyzing specimens with the minimum values of the ratio of $^{27}\text{Al}/^{24}\text{Mg}$ [12].

2.3 Physical Parameters of the Solar System

The Solar system has the following most important physical characteristics.

1. The planetary rotation around the Sun occurs in the same direction as the Sun's rotation.
2. All planets rotate round their axis in the same direction as the Sun rotates, except for Venus and Uranus.
3. The planets are distributed around the Sun non-randomly. The planetary distances from the Sun can be described by empirical equations, which have been obtained by different authors.
4. The planets are divided into two groups: 1—the outer planets, which have large masses and whose compositions are close to the solar composition; 2—the inner planets, with masses of 0.45 % of the Solar system mass and whose compositions significantly differ from the composition of the rest of the Solar system.
5. 98.7 % of the Solar system mass is concentrated in the Sun and only 1.3 % of the mass is concentrated in the planets, whereas 98 % of the angular momentum belongs to the outer planets.

The first mathematical approximation of the relation for the distances of the planets from the Sun is known as the Titsius-Bode law, which is as follows:

$$R_{n+1}/R = b,$$

where n —planetary number, b —empirical parameter. The values of b for different planets are presented in Table 2.3 [13].

From the table it is seen that the value of this parameter is not constant, but varies: $1.4 < b < 2$. Furthermore, many researchers have attempted to relate the planetary distances from the Sun with the process of planetary formation [13]:

Schmidt attempted to refine the empirical relation of Titsius-Bode. His equation was as follows:

$$\sqrt{R_n} = a' + b'.$$

This equation satisfactorily describes the planetary distances from the Sun, if the parameters a' and b' can be determined separately for the outer planets and planets of the Earth's group (Tables 2.4 and 2.5) [14].

Table 2.3 The values of the parameter b in the Titsius-Bode equation [13]

Planet pairs	b	Planet pairs	b	Planet pairs	b
Venus–Mercury	1.87	Asteroids (Cercera)–Mars	1.82	Uranus–Saturn	2.00
Earth–Venus	1.38	Jupiter–Asteroids	1.88	Neptune–Uranus	1.58
Mars–Earth	1.52	Saturn–Jupiter	1.84		

Table 2.4 The distance between the outer planets and the Sun, calculated using the Schmidt equation [14]

Planet	Rtheor. AU	Rfact. AU	Discrepancy (%)	R Titsius-Bode AU
Jupiter	5.20	5.20	0	5.20
Saturn	10.76	9.54	13	10.0
Uranus	18.32	19.19	−5	19.6
Neptune	27.88	30.07	−7	38.8
Pluto	39.44	39.52	0.2	77.2

Table 2.5 The distance between the inner planets and the Sun, calculated using the Schmidt equation [14]

Planet	Rtheor. AU	Rfact. AU	Discrepancy (%)	R Titsius-Bode AU
Mercury	0.39	0.39	0	0.4
Venus	0.67	0.72	−7	0.7
Earth	1.04	1.00	4	1.0
Mars	1.49	1.52	−2	1.6

Besides the relations presented above, the planetary distances from the Sun can be accurately described by the logarithmic spiral equation, suggested by us:

$$R = 0.225(\exp(0.172\varphi)), \quad (2.1)$$

where φ —angle of the ray turning round the polar spiral; R —distance of the planet from the Sun, AU.

It should be noted that Eq. (2.1) does not describe the planetary space location, only the values of their orbits. Equation (2.1) represents the empirical dependence of the planetary distances from the Sun, identical to Titsius-Bode, but it is possible that the spiral distribution of the planets has a genetic sense. More on the assumption of the vortex structure of the proto-planet cloud is suggested in the models of Weizsäcker and Kouper [15].

2.4 The Mass Material Distribution in the Solar System

An important characteristic of the Solar system is the relationship between the masses of the planets and their distances from the centre of the system [14].

Moreover, the composition of the terrestrial group planets differs in principle from the composition of the outer planets and the Solar system as a whole. That could be understandable if these differences had been presented for the outer planets, but the assumption about the intrusion of alien material into the inner part of the Solar system is not real. Also unreal is the assumption about the initial lack of

the mass in the proto-planetary cloud in the supply area of growing inner planets, and about the difference in composition of the other part of the cloud.

The alternative of the initially heterogenic composition of the proto-planetary cloud is a variant that contains an assumption of the loss by the inner planets of the major part of their material during the process of the formation of the Sun and outer planets. This includes the fact that the material from the supply area was redistributed in opposite directions: between the Sun and Jupiter.

The next step consists in determining the composition of the material that was lost by the inner planets, and its mass. We assume that the composition of the cloud from which the Solar system was formed corresponds to the abundance of the chemical elements in the cosmic space. The main element in this distribution is hydrogen, which amounts to 2.8×10^8 atoms per 10,000 atoms of Si [16]. Let us further suppose that hydrogen and helium were the main elements ejected from the proto-planet cloud in the area of the inner planets during the formation of the Solar system. For comparison, we can take the iron element Fe. In the cosmic material, to every 1 g-atom of Fe is related 0.67×10^5 g-atom of H and 0.5×10^4 g-atom of He. The Earth contains 34.0 mass% of Fe, which corresponds to $6.07 \times 10^{-3} m_o$ g-atoms (m_o —Earth's mass). The amount of g-atoms H and He, for which the initial material of the Earth must contain that amount of Fe, is equal to $1.1 \times 10^3 m_o$. That value is comparable with the mass of the material, which must be at a distance, on which the Earth is located. It is impossible to explain the loss of such an amount of material by the planets of the terrestrial group through the process of the dissipation of volatile components from the atmospheres of the formed planets.

2.5 The Nature of the Asteroids Belt

The active role of Jupiter in the formation of the Solar system is evidenced by the fact that, during the formation process, there occurred a significantly sharp boundary, which was fixed in space by the asteroids belt. The nature of that boundary in all models of planetary formation is not discussed. We can assume that it in fact presents a zone of gravitational equilibrium between the Sun and Jupiter, which existed during the process of simultaneous growing. The location of this zone was not fixed. The Sun's gravitational pull grew more quickly than that of Jupiter, and therefore the gravitational equilibrium zone moved in the direction from the Earth to the belt of asteroids. We can assume that Mars, during its formation, was in the area of Jupiter's attraction. This makes the nature of asteroids belts more understandable. They can be considered as pre-planetary bodies for the planets, which were formed at the initial stage of the planets' formation [17]; they occurred in the zone of gravitational equilibrium, and they could not form together as a planet, whose location would be between Jupiter and Mars.

2.6 The Possible Mechanism of the Formation of the Sun and Planets

As mentioned in the chapter above, in discussing the role of the supernova explosion in the formation of the Solar system, we concluded that the presence of short-living isotopes of aluminum, iron and manganese was evidently the basis for the formation of the Solar system from material thrown out by the supernova explosion. That assumption radically changed our ideas about the mechanism of the formation of the Sun and the planets of the Solar system. Firstly, the duration of the period when the main mass of the initially dissipated proto-solar material was concentrated into the growing Sun decreases sharply. That period is no more than 10^6 years, which is the time after the supernova explosion up to the occurrence in the near-solar space of the material of CAI. That velocity of the Sun's material accumulation could be achieved, probably, only in the case that the material ejected by the supernova explosion was in the form of a jet, which was transformed into a spiral vortex by the action of gravitational and electromagnetic forces, as a result of which the material moving along the spiral became concentrated in its centre. Secondly, because the proto-planetary material was in a gaseous state, the initial and boundary conditions that were in the models of the planetary formation from the gas–dust cloud [13, 18, 19] were changed. It can be assumed that the proto-planetary clots of the material could appear in the form of turbulent perturbations in the spiral vortex, from which the Sun formed. This is proved by the fact that the largest satellites of Jupiter are located on the branches of the logarithmic spiral. Thirdly, the formation of these proto-planetary clots is also supported by the distances distribution of Jupiter's satellites, which is described by the logarithmic spiral equation. Thirdly, the proto-planetary clots were also formed over a period of 10^6 years, and in that time interval the main mass of the material that had been in a gaseous state in the area of the formation of the terrestrial group planets, was absorbed by the growing Sun. The suggested variant of the formation of the Solar system does not disagree with the data that Chambers presented as the reason for the formation of the Solar system from the dust molecular clouds [2]. It must be noted that only about 4 % of the main part of young stars have planetary systems, which is evidence that the conditions in which planetary systems can be formed are very rare. Therefore the existence of young stars having gas–dust disks, but having no planets, can be considered as a situation in which the necessary conditions were not realized. An additional argument, which satisfies the possibility of the Solar system's formation from the supernova material, is the fact that the planetary systems could have stars no older than $\sim 10^6$ years, from which it flows that the average velocity of the material accumulation by the central star forming in such systems would achieve 10^{-7} times the Sun's mass per year [2]. Taking into account that the relation of the accumulation velocity to time has a maximum, and that the maximum value of the velocity at that point can be significantly larger, than its average value, therefore the most Sun's mass could be absorbed during the first million years from the moment of the supernova explosion.

The most complicated question for models of planetary formation from the initial homogeneous near-solar disk is to explain the characteristics of the Solar system's distribution of angular moment. Because the Sun together with the proto-planetary disk is an isolated system, it has to fulfill internally the condition of moving moment conservation, or a mechanism for transformation into another form of energy must exist. One possible variant to explain the distribution of the angle moment can be suggested based on the mass distribution of the Solar system. From that distribution, it follows that the large material mass that was initially located in the interval between the Sun and the Earth was absorbed by the Sun. Together with this mass, also transferred into the Sun was kinetic energy, which was transformed into thermal energy and was then used for the heating of solar material. Therefore it can be assumed that the values of 98 % of the moving moment, which are presently linked with the moving of the outer planets, are really only equal to 2 % from the initial moment of the proto-planetary cloud. The remaining 98 % was transformed into thermal energy by the formation of the Sun.

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