

**WHAT KIND OF ACCRETION MODEL IS REQUIRED FOR THE SOLAR SYSTEM?** G. K. Ustinova, Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow 119991 Russia; e-mail: [ustinova@dubna.net.ru](mailto:ustinova@dubna.net.ru)

**Introduction:** The main goal of the accretion model of the Solar system must be the precise conception of sources and mechanisms of formation of the observable mineralogical, chemical and isotopic composition of its matter. The starting point of the model is the isotopic and elemental composition of the primordial matter, i.e., of the protosolar and protoplanetary nebulae, and its transformation during such global processes as collapse, emergence of the protosun and its further evolution. As supposed in the early condensation models (e.g., [1-3]), the energy of the gravitation collapse was sufficient for evaporation of all the protosolar dust which then recondensed under the equilibrium conditions in the accretion disk and led to the isotopic and chemical homogeneity of the protoplanetary nebula. The numerous isotopic anomalies in meteorites forced everyone to refuse such a hypothesis. The gas-dust protoplanetary cloud is the main initial conception of all the contemporary models of origin of the Solar system. The thermodynamic accretion models at the T-Tauri stage of the solar evolution have turned out to be the most elaborated ones (e.g. [4-6]). They presented wide comprehension of the thermodynamic processes in the accretion disk and inferred many important factors of differentiation of matter in the early Solar system.

**What else should be done ?** Is there an approach to the further improvement of the models ? Indeed, the existing thermodynamic models are hydrostatic ones: the constant accretion flux of matter onto the Sun through the disk is considered. The role of the Sun is reduced to the outside heating of the disk by solar radiation. Meanwhile, beginning from the FU-Orion stage and during the T-Tauri stage of the solar evolution, the powerful fluxes of the matter reprocessed in the protosun interior returned to the accretion disk. The importance of such processes in the formation of the composition of the protoplanetary matter was noted in [7, 8]. Thus, the further thermodynamic model must be, at least, the hydrodynamic one. Moreover, the matter in the entrails of the protosun became ionized plasma, the differential rotation of which led to generation of the magnetic fields and triggering of the hydromagnetic dynamo of the protosun [9, 10]. Therefore, the distribution of the matter during the accretion in the early Solar system had to obey the regularities of the magnetic hydrodynamics, i.e., the accretion thermodynamic model should be the magneto-hydrodynamic one. It is evident that the solution of the system of magneto-hydrodynamic equations (interrelated equations of hydrodynamics and electrodynamics) leads to more complex conditions during the accretion, especially, most likely, to non-uniform distribution of matter in the accretion disk. However, above all, perhaps, the most important consequence of the magneto-hydrodynamic consideration of the processes in the early Solar system is the particular role of shock waves in the initial isotopic fractionation of the primordial matter.

**A feature of shock waves in magneto-hydrodynamics:** The shock waves accompany practically all astrophysical processes. Concerning the Solar system, the decisive importance of the accretion shock waves in formation of chondrules and coagulation of dust particles is generally

supposed (e.g. [7,11]). Due to conversion of the kinetic energy of the waves to the thermal one of the matter, the specific PT conditions for melting, vaporizing and recondensing the solid phases were generated. Surely, similar shock processes had to take place in zones of the protosolar wind interaction with the internal boundary of the accretion disk, as well as in the zones of reverse infall of the bipolar outflows onto the accretion disk [7, 8].

On the other hand, starting from the earliest astrophysical works (e.g. [12]), a specific role of the shock waves in acceleration of generated particles is supposed. Indeed, the energies of  $\sim 10^9$  GeV, which are observed in the contemporary cosmic rays, cannot be achieved in any astrophysical processes. In this connection, the generated particles are assumed to be accelerated up to such high energies by strong shock waves during their further propagation in the interstellar space. However, the initially used acceleration mechanisms, consisting in direct transfer of the shock wave kinetic energy to the particles (e.g. [13]), turned out to be ineffective ones due to rapid dissipation of the shock wave energy in medium [14].

Only the magneto-hydrodynamic consideration of the shock wave propagation (the so-called collisionless shock) elucidates the problem [15-17, etc.]. Unlike shock wave interaction with neutral medium through pair collisions of particles, the ions during shock propagation in the charged plasma interact with magnetic turbulence, generated in the narrow (of the order of ion gyroradius) shock front, acquiring an energy increment at every traverse of the front. The ions with higher energies and heavy ions with longer paths are more frequently accelerated, because they could enter the shock front more frequently and from larger distances. Thus, due to shock wave acceleration, the energy spectrum of ions becomes harder and flatter (low spectral index  $\gamma$ ). Since the free path of heavy ions is an increasing function of energy  $R=p/Ze$  (where  $p$  is the momentum of ion proportional to  $A$ , and  $Ze$  is its charge), the effect of acceleration depends on the ratio  $A/Z$ , i.e. the energy spectrum of the shock wave accelerated particles must be not only more rigid but also enriched with heavier ions. If the ions underwent shock wave acceleration  $n$  times, their spectrum had to be enriched with heavier ions in proportion to  $(A/Z)^n$ . It is known, for instance, that solar energetic particles are enriched with heavy ions proportionally to  $A/Z$  or  $(A/Z)^2$ , depending on possible shock wave acceleration in the corona (before injection) or/and in the heliosphere [18].

#### **Why is it important for the early Solar system?**

1. D. D. Clayton was apparently the first who pointed out the time between generation of isotopes and their fixation in solid phases as the most mysterious and the least studied period in cosmochemistry [19]. It is just the time when the initial elemental and isotopic relations underwent alterations conditioned by numerous differences of physical and chemical properties of the elements and isotopes, as well as of their bearing phases. Nevertheless, it became customary to analyze the relationships of the generated isotopes instead of estimating their absolute amounts. Such an approach is based on the assumption that the ratio of the isotope production rates is determined by the ratio of their

production cross sections, averaged in accordance with the energy spectrum of nuclear active particles, because the flux of the latter, commonly unknown, is reduced. However, in the light of Clayton's remark, just the absolute amounts of isotopes, generated in some processes, play sometimes a crucial role in the solution of different problems. The striking example is LiBeB: no probable model of Li (especially  ${}^7\text{Li}$ ) generation provides its observable abundances without disturbances in the ratios of other isotopes of those elements and extinct radionuclides [20]. Meanwhile, the extinct radionuclides and tracks of VH-nuclei evidence very rigid radiation conditions in the early Solar system ( $\gamma \sim 1.2$  of power-law energy spectrum  $F(>E_0) \sim E^{-\gamma}$ , whereas  $\gamma = 2.5$  is for the galactic cosmic rays, and  $\gamma > 3$  is for the solar cosmic rays) [21]. If it is conditioned by shock wave acceleration, the integral fluxes of nuclear active particles above the threshold energy  $E_0$  of the spallation reactions grow up to one-two orders of magnitude. It leads to LiBeB generation in quantities much higher than the observed ones [22, 23]. Thus, the puzzle is not in the way of formation of large amounts of  ${}^7\text{Li}$  but in the mechanisms of its preservation in excess of other isotopes. Apart from different physical and chemical features of LiBeB and their bearing phases, the rate of  ${}^7\text{Li}$  decay in a proton-rich medium is lower than those of  ${}^9\text{Be}$ ,  ${}^{10}\text{B}$ ,  ${}^{11}\text{B}$ , and  ${}^6\text{Li}$ , but its acceleration in shock waves is the highest due to the highest ratio  $A/Z = 2.33$ . Owing to its preferable acceleration,  ${}^7\text{Li}$  is faster removed into the cold ( $T < 2 \cdot 10^6$  K) regions, where its proton-induced destruction ceases. One may see in [23 and ref. therein] that the presence of shock wave reprocessed matter in the protosolar or/and protoplanetary nebulae explains many known isotopic anomalies of extinct radionuclides, light elements and noble gases in meteorites.

2. Every accretion model must be based on some initial elemental and isotopic relationships, and commonly the systematics of the cosmic abundances (e.g., [24]) is used. However, if the reservoirs of the shock wave reprocessed matter existed in the early Solar system, they would contain the quite different relationships of elements and isotopes, in particular, the matter would be fractionated in proportion to  $(A/Z)^n$  in accordance with  $n$  acts of acceleration. In the case of  $i$  and  $j$  isotopes of the same element it would be the earliest mass fractionation  $(A_i/A_j)^n$  of the generated matter. Thus, the nine-isotope xenon system of the Earth and Mars atmospheres turned out to be five-fold mass-fractionated in comparison with its solar signature [25]. It is reasonable to suggest that the planets were formed in the regions of the protoplanetary nebula, the matter of which was strongly reprocessed by shock waves. Such regions would be enriched with iron nuclei (the latter make up  $\sim 100\%$  of the spectrum of charged cosmic rays above  $10^7$  GeV [26]), so that just such regions could serve as accretion centers of planets, in particular, of those with iron cores. The similarity of the isotopic signatures of iron meteorites and the Earth [27] support this concept. Earlier, at the stage of the protosolar nebula, iron-enriched zones of supersonic turbulence in the discarded envelope of the last supernova could result in the dynamic instability in the nebula and cause its collapse.

It should be noted that shock wave fractionation is especially high in the weakly ionized medium, when the

effective charge  $Z^*$  of ions is small. Such a fractionation is observed in the contemporary solar particle radiation and naturally always existed in the heliosphere [18, 28].

**What else should be accounted for if the recent nearby supernova explosion took place?** The extinct short-lived radionuclides in the primordial matter testify surely that such a supernova played its important role in formation of the Solar system. Probably, its explosion triggered the collapse of the protosolar nebula, e.g., due to the above-mentioned iron enriched zones of supersonic turbulence in the discarded envelope, or because the expanded envelope of the supernova streamlined and compressed the protosolar molecular cloud up to its collapse [29,30]. If the last scenario was operative, the matter of the supernova should be considered as a boundary condition in the accretion model. The analysis of formation of the extinct radionuclides leads to the conclusion that the last supernova was a carbon detonation supernova, which could not "survive" during carbon fusion and completely disintegrated [31]. As a result, the protosolar molecular cloud turned out to be surrounded with a huge amount of the unburned carbon, the part of which was involved into the cloud during the collapse or at the reentry of bipolar outflows into the accretion disk, enriching the Earth with carbon during its formation in the thermal conditions of the accretion disk. Another part of the carbon, which was the last to accrete in the conditions of free gravitation at much lower temperatures formed the matter of carbonaceous chondrites, in particular, CI-chondrites.

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\*\* Technical translation error: replace, please, "fission" by "spallation" practically throughout the text of that paper.