POSSIBLE ROLE OF THE TYPE Ia SUPERNOVA EXPLOSION IN FORMATION OF 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

Introduction: The solar system is a valuable, rich astrophysical laboratory because it represents the final results of wide-ranging nebular processes leading to formation of stars with planetary systems. The main and the most important link of investigations is the isotopic and elemental composition of the primordial matter. The contemporary level of knowledge is based on the conception that the primordial matter is founded on the matter of the giant molecular gas-dust nebula, which was distributed homogeneously with the products of the nucleosynthesis of about ten of supernovae during ~10 Ma of its existence before turbulent dissipation. However, the numerous isotopic anomalies in meteorites, which are conditioned by the decay of some extinct radionuclides, suggest that, at least, one of the supernovae had been exploded shortly before the collapse of the protosolar nebula. The matter of the last supernova cannot yet be mixed evenly with the matter of the molecular cloud: it rather flowed round, surrounding the cloud gradually [1]. The intervals of formation of the short-lived extinct radionuclides of ^{41}Ca, ^{26}Al and ^{53}Mn testify to the last supernova explosion about 1 Ma before the formation of the solid phases of the primordial matter [2]. The absence of heavier extinct radionuclides (the products of *r*-process) with the similar intervals of formation indicates that the last supernova was the type Ia supernova (the so called, carbon-detonation supernova), which could not survive the carbon explosive burning and was fully disrupted [2,3]

Type Ia Supernovae (Sne Ia) turned out to be the ideal objects for estimating the Hubble constant, and so, the properties of these supernovae are being studied intensively over last years [4]. For the most part, Sne Ia are the explosions of white dwarfs, consisting of carbon and oxygen, that have approached the Chandrasekhar mass, $M_{Chan} \approx 1.39\ M_{\odot}$. Just because of about equal mass and composition, the Sne Ia are considered as “standardizable candles”: their calibrated light curves have become a major tool to determine the cosmological expansion rate, its variation with look-back time and also the geometrical structure of the universe [4,5 et al.]. At the explosive burning of carbon and oxygen, releasing the energy of ~10^{51} erg, all the intermediate-mass elements like Mg, Si, S, Ca are synthesized, but the doubly-magic nucleus ^{56}Ni is produced with the highest probability. During 6.1 days it decays to ^{56}Co, which, in its turn, decays to ^{56}Fe over 77 days. Thus, depending on the initial C/O composition of white dwarfs, the Sn Ia explosion produces 0.4-0.6 $M_{\odot}$ of ^{56}Fe, substantial amounts of the intermediate-mass elements, and, besides, some unburned amounts of C+O can be ejected [6,7 et al.].

The peculiarities of the Sn Ia may be suggested to specify the uniqueness of the solar system among the other forecasting planetary systems. At least, three important aspects may be pointed out.

Heterogeneity of Accretion: The current concept is that the chemical and isotopic composition of the primordial matter was similar to the contemporary solar one [8] in many respects. It is based on the supposed absence of essential fractionation at the collapse stage of the molecular gas-dust clouds during the formation of the planetary systems [9]. However, the SN Ia explosion just before the origin of the solar system, especially, if its matter surrounded the collapsing nebula, led to rather a heterogeneous accretion: the specific matter of SN Ia (e.g., the ratio of Fe to Si-Ca is by about a factor of 2-3 higher than in the solar composition [7]) had accreted mainly at the concluding stage of the formation of the solar system, enriching the latter with iron, intermediate elements, as well as with unburned C and O. It looks tempting that just the enrichment of the upper mantle of the earth with the unburned C and O has provided the basis for some pre-biological background and subsequent origin of life on the earth.

Rigidity of the Energy Spectrum of Particles: The Sn Ia explosion had established peculiar radiation conditions in the early solar system [10]. The tremendous explosive shock wave and supersonic turbulence had resulted in acceleration of particles in the cosmic plasma with forming a power-law energy spectrum $F\ (>E_0) \sim E^{-\gamma}$ of very high rigidity ($\gamma \rightarrow 1$) [11]. Shock waves pick up new particles from the background plasma and pump over the particles from the low energy range of the spectrum to the high energy one. That leads to the enhancement of fluxes of nuclear-active particles (and, therefore, of spallation production rates of isotopes) above the energy E_0 (e.g. above the threshold energy of nuclear reaction) by one-two orders of magnitude [12]. That strongly increases the share of the spallation processes in the last nucleosynthesis event of the primordial matter of the solar system. For instance, the origin of light elements Li, Be and B in spallation reactions, as suggested by Fowler in the middle of the last century [13], can in no way be achieved under the average proton fluxes of ~10^{19} cm^{-2}, forecasted for the early solar system [14]. However, the consideration of the problem in the high radiation conditions of the supernova explosion not only ensures the observed abundances of the light elements, but it also allows us to understand why ^{7}Li had survived better than other isotopes [15].

The increasing rigidity of the energy spectrum of nuclear-active particles changes the weighted (according to the spectrum) mean values of the production cross sections of many isotopes, whose excitation functions are sensitive to the shape of the spectrum. It produces changes in the isotope and element relations, i.e. isotopic anomalies, in the matter reprocessed by the shock waves (e.g. in the expanding matter of Sn Ia) in comparison with the matter of the main volume of the gas-dust cloud. Therefore, the search of such anomalies in meteorites makes it possible to identify the fresh-generated matter of Sn Ia. Indeed, the analysis of the extinct radionuclides in meteorites of different types shows the difference of radiation conditions inside the zones of their condensation: the matter of carbonaceous chondrites was condensed under the rigid ($\gamma \sim 1.2$) radiation conditions, i.e. from the matter of Sn Ia (?), whereas the matter of ordinary chondrites was condensed under the soft ($\gamma \sim 4.2$) ones, i.e. inside the gas-dust molecular cloud (?) [12]. In differential meteorites some minerals, condensed under quite different radiation conditions, are observed: olivines - at $\gamma \sim 4.2$, but sulfides and phosphates in the same meteorites, as well as in the Willey iron meteorite, - at $\gamma \sim 1.2$-2.5. It is possible if accretion of the differential meteorites took place in the regions where the Sn Ia matter was blended with it of the molecular cloud, i.e. in their interface regions [12]. It is in accordance with the scenario [1] that the supernova matter surrounded the cloud.

Enrichment of the Spectrum with Heavy Ions: Another remarkable feature of shock wave acceleration of particles is enrichment of their spectrum with heavier nuclei. Indeed, the free path of multiply charged ions is an increasing function of energy: $R=p/Ze$ (where p is the momentum of particles proportional to A, and Ze is the ion charge), and the effect of acceleration depends on the ratio of A/Z: ions with higher A/Z enter the preshock area from farther distances, and so, they are accelerated more frequently [16]. Study of air showers, induced by charged cosmic rays, shows that at ultrahigh energies ($\geq 10^7$ GeV) the energy spectrum of the particles consists of iron nuclei up to ~100% [17,18]. This is interpreted as an evidence for the acceleration of the primary cosmic-ray particles as fully ionized nuclei in turbulent magnetic fields (e.g. in supernova remnants). This effect is also well known in the contemporary solar cosmic rays: their SEP component (solar energetic particles) is enriched with heavy ions proportionally to A/Q or A/Q^2 (where $Q < Z$ is the ion charge) depending on their possible acceleration in the corona (before injection into the heliosphere) or/and in the interplanetary magnetic fields [19, 20 et al]. It means that such a fractionation of particles depends also on number of the shock-wave acceleration acts. Therefore, the degree of fractionation of the matter in different isotopic reservoirs of the solar system is determined by the degree of its shock-wave reprocessing before and during its accretion in different regions of the protoplanetary nebula. For instance, Xe of the Earth and Mars atmospheres may be considered as the primordial Xe of the solar composition which had undergone five acts of shock-wave acceleration in some processes during the formation of the solar system [21]. A lot of other isotopic evidence might be found.

Possible scenario: Apart from isotopic effects in primordial matter, Sn Ia explosion opens, apparently, a clue to the origin of iron meteorites: the large quantity of synthesized and accelerated iron nuclei were the first that penetrated into the collapsing protoplanetary cloud and, being captured by supersonic turbulence, they became centers of iron parent bodies. In some cases of especially huge vortex the captured iron nuclei underlay the metallic cores of some planets, which further were built up due to magmatic differentiation. The intermediate and light nuclei of Sn Ia explosion reached the accreting system rather later. Because of the turbulence drawing into the central plane of the accretion disk, they had played a key role in formation of the earth group planets under the reducing conditions being typical for such heliocentric distances. But the most part of the unburned C of the exploded Sn Ia had accreted at the conclusive stage of accretion in the conditions of low temperatures and free gravitation that had provided the formation of carbonaceous chondrites.

References: [1] Schramm D. N. (1982) *Protostars and Planets*. M.: Mir, 440-457. [2] Ustinova G.K. (2002) *Doklady RAS, 382*, 242-245; *LPS XXXIII*, # 1015. [3] Ustinova G.K.(2002) *Geochemistry, 9*, 915-932. [4] Branch D. (1998) *Ann. Rev. Astron. Astrophys., 36*, 17-55. [5] Branch D. and Tammann G.A. (1992) *Ann. Rev. Astron. Astrophys. 30*, 359-389. [6] Gamezo V.N.et al. (2003) *Science, 299*, 77-81. [7] Thielemann F.-K. et al. (2005) *Proc.22nd Int.Nucl.Phys.Conf.*, Goteborg, 301-328. [8] Grevesse N. and Sauval A.J. (1998) *Space Sci.Rev., 85*,161-174. [9] Cassen P. et al. (1985) *Protostar and Planets, Tucson : UAP*, 448-483. [10] Kashkarov L.L. and Ustinova G.K.(2000) *Doklady RAS, 372*, 659-662; *LPS XXXI*, #1046. [11] Ellison D.C. and Eichler D. (1984) *Ap. J. 256*, 691-701. [12] Ustinova G.K. (1995) *Solar Syst. Res. 29*, 345-356; *Izv.RAS. Ser.Phys. 59*, 166-170. [13] Fowler W.A. et al. (1955) *Ap.J. (Suppl), 2*, 167-194. [14] Audouze J. (1970) *Astron.Astrophys. 8*, 436-457. [15] Ustinova G.K. (1996) *Solar Syst. Res. 30*, 483-495; (1998) *Doklady RAS,358*, 391-394. [16] Eichler D. and Hainebach K. (1981) *Phys.Rev.Lett. 47*, 1560-1563. [17] Goodman J.A. et al. (1979) *Phys.Rev.Lett. 42*, 854-857. [18] Lindner A. (2001) *CERN Courier, 41, N 9*, 17-19. [19] Meyer J.-P. (1985) *Ap.J. (Suppl), 57*, 151-171; 173-204. [20] ACE News (1998-2005) http://www.srl.caltech.edu/ACE/ACENews/. [21] Ustinova G.K. and Marti K. (2000) *LPS XXXI*, #1230.