Translated from *Uspekhi Khimii*, 45, 329 - 353 (1976) U.D.C. 547.466

Prebiological Synthesis of Aminoacids and the Search for them in Meteorites and Lunar Rocks

A.T.Soldatenkov and I.A.Sytinskii

New data on various prebiological syntheses of aminoacids and the detection of very small amounts of aminoacids in meteorites and lunar rocks are reviewed. Data are presented concerning the possible precursors of these aminoacids. The hitherto obscure problem of the mechanisms of the formation of aminoacids under the conditions of prebiological synthesis is considered.
The bibliography includes 156 references.

CONTENTS

I. Introduction 168
II. Aminoacid precursors. The search for aminoacids in meteorites and lunar rocks 168
III. Prebiological synthesis of aminoacids 175

I. INTRODUCTION

By 1974 fifty years had elapsed since Academician A.I.Oparin's theory of the origin of life was proposed[1]. The Soviet biochemist was the first to formulate a hypothesis concerning the nature of the primary atmosphere on Earth and the possibility of forming complex compounds such as proteins and nucleic acids from the elements as a result of chemical and physicochemical processes in the atmosphere and in the ocean. These processes would have occurred spontaneously under the influence of ultraviolet radiation from the sun, the energy of electric discharges, volcanic heat, and the ionising radiation from terrestrial radioactive rocks. Oparin's idea, subsequently supported by Haldane[2], received the first experimental confirmation after 30 years as a result of the studies carried out by Miller, who succeeded in simulating the formation of biologically important molecules in a non-living system imitating Earth's primitive atmosphere[3,4].

Sciences such as organic and bio-organic chemistry, biochemistry, cosmochemistry, astrophysics, selenology, and others have played an appreciable role in the elaboration and development of the theory of the origin of life. The fundamental studies in this field are being prosecuted in two directions. The first direction, involving synthetic research, was initiated about 20 years ago. Theoretical and experimental investigations led to the accumulation of an enormous amount of data on the synthesis of aminoacids, polypeptides, purine and pyrimidine bases, porphyrins, and monosaccharides under the conditions of the primitive planet as reproduced in the laboratory[5-9]. The development of this research was stimulated afresh by recent radioastronomical observations, which indicate the presence in interstellar matter of molecules important for chemical evolution, such as those of ammonia, water, hydrogen cyanide, cyanoacetylene, acetaldehyde, and others[10].

The second direction involves analytical research. Here studies in the last 5–7 years have been concentrated on the analysis of the carbonaceous material in meteorites and lunar rocks, as well as interstellar matter. Exceptionally important results have been obtained in this field, which permit an answer to the questions whether or not organic compounds of extraterrestrial origin exist, what is their composition, and how they have been formed.

Both prebiological synthesis and analysis of aminoacids are considered in the present review. Recently, all the protein and a number of non-protein aminoacids have been successfully synthesised by non-biological methods or have been detected in objects of extraterrestrial origin (lunar rocks, meteorites), but the mechanisms of formation of these aminoacids have still been little studied.

II. AMINOACID PRECURSORS. THE SEARCH FOR AMINOACIDS IN METEORITES AND LUNAR ROCKS

Cosmic Space

The initial elements required for the synthesis of organic compounds (H, C, O, and N) are formed on a cosmic scale in the central regions of stars at very high temperatures. Diffusional and convective processes displace them towards the surfaces of stars. In stellar atmospheres at relatively low temperatures diatomic and triatomic species such as C_2, C_3, CH, CH_2, CN, CO, CO_2, NH, OH, and CH_4 may be synthesised. Astronomical observations have shown that various stellar processes probably lead to the ejection of these and other compounds as well as atoms into the space around the stars and the interstellar space[11]. Among processes of this kind, one may include the explosion of novae and supernovae, stellar pulsations, flares, and winds, and the migration of mass as a result of the pressure difference between the hot surfaces of stars and the cold interstellar space.

Oró[10], who considered the relative abundances of certain chemical compounds and their stability with respect to heat and light, concluded that stable species of the type CO, CN, CH, C_2, C_3, and others, which are ejected into interstellar space, are subsequently hydrogenated and hydroxylated with formation of organic molecules: CH_2O, CH_3OH, HCOOH, HCN, $HCONH_2$, CH_3CHO, HC_2CN, etc.

The following species have been detected by optical measurements in the gaseous components of interstellar clouds and gas nebulae: CH, CN, CH^+, H_2, and CO.[12] Following the development of microwave spectroscopy, it became possible to extend greatly the knowledge of the composition of interstellar matter. Between 1968 and 1970, compounds such as ammonia[13], water[14], formaldehyde[15] (the first organic molecule discovered in interstellar space), and hydrogen cyanide[16] (the second organic

molecule found in space) were detected. Turner [17] observed in 1970 an emission spectrum which corresponded to cyanoacetylene. The above five polyatomic molecules discovered in the interstellar space are probably the most important aminoacid precursors; formaldehyde is most widely distributed in space and is frequently called the "cosmic molecule". Together with hydrogen and hydroxy-radicals, it is probably a normal constituent of many regions of the Milky Way [10].

Table 1. Certain chemical compounds detected by radiospectroscopy in cosmic space.

Year of discovery	Compound	Formula of compound	Wave-length, mm	Concn. of cpd.*	References
1968	Ammonia	NH_3	13	$1\cdot10^{-7}$	12,13
1968	Water	H_2O	13	—	14
1969	Formaldehyde	CH_2O	62	—	15
1970	Carbon monoxide	CO	2.6	$1\cdot10^{-3}$	12,18
1970	Cyanyl radical	CN	2.6	—	19
1970	Hydrogen cyanide	HCN	3.4	$1\cdot10^{-7}$	12,16
1970	Cyanoacetylene	$HC\equiv C-CN$	33	—	17
1970	Methanol	CH_3OH	360	$1\cdot10^{-7}$	12,20
1970	Formic acid	HCOOH	180	—	21
1971	Formamide	$CHONH_2$	65	—	22
1971	Methylacetylene	$HC\equiv C-CH_3$	3.5	—	24
1971	Acetonitrile	CH_3CN	2.7	—	23
1971	Acetaldehyde	CH_3CHO	280	—	10
1971	Thioformaldehyde	CH_2S	95	—	10
1972	Hydrogen sulphide	H_2S	1.7	—	10
1972	Methyleneimine	CH_2NH	56	—	10

*The concentration of hydrogen was adopted as unity.

By the beginning of 1974, 27 cosmic molecules had been discovered (Table 1). The data in Table 1 show that interstellar matter includes all the initial compounds which may serve for the synthesis of biochemically important substances. The problem of the ways in which these initial compounds are synthesised remains open. There exist two hypotheses concerning the formation of interstellar molecules. The first claims that they may be synthesised under the influence of cosmic rays on the surface of dust particles of interstellar nebulae or meteorites from the CO and H_2 adsorbed on them by a mechanism close to that of the familiar Fischer–Tropsch synthesis [25]. The other (ionic) hypothesis presupposes a homogeneous synthesis of complex cosmic molecules as a result of collisions between ions or simple molecules in the gas phase. Thus it is believed that formaldehyde may be formed in space via the following mechanism [12]:

$$H_2^* + H_2 \rightarrow H_3^* + H;$$

$$H_3^* + CO \rightarrow H_3CO^*;$$

$$H_3CO^* \rightarrow H_2CO + H^*.$$

According to this mechanism, one may expect the existence in space of HCO^+ ions, which are formed in another decomposition reaction: $H_3CO^* \rightarrow HCO^* + H_2$. Indeed, Buhl and Snyder [26] detected this ion in 1970 at a wavelength of 3.4 mm.

Comets

The primary compounds may have appeared on Earth's surface in different ways. For example, they might have been introduced when the planets of the solar system passed through interstellar clouds and gas nebulae. One cannot rule out the possibility that the organic substances in comets and meteorites may have served as the sources of the simplest aminoacid precursors on Earth. For example, it is believed that the isotopic composition of the carbon in comets is similar to that on Earth [27].

The orbits of certain comets adjoin Earth's orbit and may even intersect it. This suggests the possibility that a certain amount of the material from comets may reach our planet by a direct collision between the comet and Earth or following the incidence on Earth of meteor streams (showers) and other residues from the comet. Comets contain significant amounts of organic compounds. The nucleus of the comet probably includes H_2O, HCN, NH_3, CO, C_2N_2, CH_4, and C_2H_2. [27] The central body of the comet is surrounded by a rarefied atmosphere (an envelope of vaporised molecules), which emits a beam of rays (the tail) in the direction away from the sun. The main component of the gaseous envelope (the "coma") is atomic hydrogen [28]. Other species are also present: H_2, OH, OH^+, O, CN, C_2, C_3, CH_2, CH, CH^+, CO^+, NH, NH_2, etc. [27]; the presence of C_2H radicals is also possible. CO^+, N_2^+, CO_2^+, CH^+, OH^+, and CN have been detected in the comet's tail. These chemical species may arise on photodissociation or ionisation of stable initial molecules. It is also possible that they are formed as a result of chemical reactions occurring on the surface of the nucleus (for example, under the influence of the solar wind).

Meteorites

Meteorites frequently contain the so called carbonaceous material. Carbonaceous chondrites are particularly rich in this material (up to 5 wt.%). [29] It has been established that the carbonaceous material consists of volatile and involatile organic compounds. In this connection, carbonaceous chondrites are of particular interest for the investigation of aminoacid precursors. Data on the nature of the organic compounds in meteorites have been fully reviewed by Vdovykin, who surveyed scientific data which have accumulated on this problem since 1806. [30] Studies in recent years have shown that meteorites contain not only aminoacid precursors (for example, alkanes ranging from C_1 to C_{26}) [30,31] but also aminoacids themselves.

Aminoacids were found previously in many carbonaceous chondrites, but until 1970 the majority of investigators held the view that these aminoacids are probably of terrestrial biological origin and that they are present in the material of the meteorite as a result of contamination [32]. The aminoacid composition of the mixture closely resembled that of human fingerprints. Furthermore, it was shown that aminoacids detected in two meteorites had mainly the L-configuration [33].

Indeed, the problem of biological contamination continues to arise at various stages of experiments on specimens of extraterrestrial origin. Biological impurities can completely distort the true qualitative and quantitative composition of the aminoacid mixture [32,34]. If criteria were available for distinguishing between molecules of biological and non-biological origin, it would be possible to detect reliably biological impurities in the aminoacid mixtures analysed. The general approach to the solution of this problem is based on the differences between the distributions of the enantiomers in the mixtures, between the molecular structures of the individual aminoacids, and between their relative amounts [35,36]. The value of this approach in determining the aminoacid source is somewhat

reduced by the racemisation processes [37-41] and the presence in certain micro-organisms (a possible source of contamination) of aminoacids having the D-configuration [42].

The distribution of protein aminoacids in man and bacteria [43] shows that, on contamination by material of human origin, one may expect approximately the following proportions of the four commonest aminoacids, namely glutamic acid : aspartic acid : glycine : leucine = 1.0 : 0.70 : 0.70 : 0.6, while on bacterial contamination we have 1.0 : 0.8 : 0.4 : 0.4.

One should note that aminoacid mixtures obtained in the analysis of contaminations by human fingerprints contain, apart from all the protein aminoacids, also citrulline and ornithine—the metabolic products of the urea cycle [44], which can also be used for the identification of impurities.

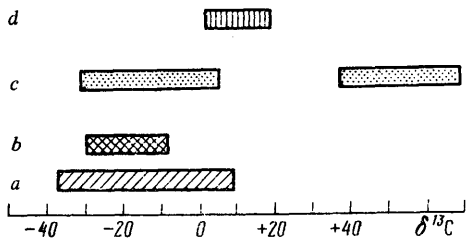


Figure 1. Isotope composition of terrestrial [*a*) total; *b*) biospheric], meteoritic (*c*), and lunar (*d*) carbon.

In the search for aminoacids of extraterrestrial origin, the study of isotopic composition may be of decisive importance. It is known [45] that most of the carbon in Earth's biosphere has an isotope composition† ranging from −29 to −8‰ [of carbon-13] (Fig. 1). The content of the heavy isotope in meteoritic carbon reaches up to +70‰. [46] Such an isotope ratio does not obtain in any of the known sources of carbon on Earth. Consequently these data might indicate indirectly the extraterrestrial non-biological origin of the aminoacids in carbonaceous chondrites. The organic substance in meteorites is also greatly enriched in deuterium [29].

The recent fall of the Murchison meteorite (in 1969) made it possible to obtain specimens with minimal biological contaminations. This carbonaceous chondrite contains 2.0 wt.% of carbon and 0.16% of nitrogen [47]. Studies on the Murchison meteorite carried out in three laboratories [47-50] established the presence of aminoacids of non-biological origin. In two investigations [47,48], the meteorite specimen was treated with water and the solution was hydrolysed and separated on an aminoacid analyser. Part of the aminoacid mixture was analysed in the form of 2-butyl-D-esters of *N*-trifluoroacetylaminoacids on a gas–liquid chromatograph combined with a mass-spectrometer [51-54].

The analysis led to the determination of six protein aminoacids with approximately equal proportions of the enantiomers and 12 non-protein aminoacids (Table 2).

† The isotope composition of carbon ($\delta^{13}C$) is quoted in parts per thousand (‰) relative to the composition of the carbonaceous material of the fossil belemnite adopted as the standard.

Gas–liquid chromatography (GLC) showed that nine aminoacids gave rise to separable diastereoisomeric derivatives (Fig. 2). They all probably exist in the form of racemic mixtures. The presence of many non-protein aminoacids in the Murchison meteorite (2-methylalanine and sarcosine, which are very rarely encountered in biological systems), the presence of all the isomers with two and three crabon atoms, and almost all the isomers with four carbon atoms, as well as the high degree of racemisation of the optically active aminoacids indicates a low probability of biological contamination of the meteorite and suggest that non-biological synthesis has been the source of the aminoacids. This conclusion is confirmed by measurements of the isotope ratio $^{13}C/^{12}C$, which show that the carbon of the Murchison meteorite ($\delta^{13}C = +4.4 - +5.9$‰) differs appreciably from the carbon of Earth's biosphere (between −8 and −29‰).

The maximum concentrations of the protein aminoacids of the Murchison meteorite were those of glycine (6 $\mu g\ g^{-1}$), alanine (3 $\mu g\ g^{-1}$), glutamic acid (3 $\mu g\ g^{-1}$), valine (2 $\mu g\ g^{-1}$), and proline (1 $\mu g\ g^{-1}$). A similar distribution of aminoacids in this meteorite was found by another group of investigators [49], who analysed it by a highly sensitive and rapid ion-exchange chromatographic method. They also analysed the Murray and Allende carbonaceous meteorites, the results for the former being analogous to those for the Murchison meteorite, while in the latter no aminoacids were detected (the specimens contained only 0.007% of nitrogen).

The total amounts of 10 aminoacids in the Murchison and Murray meteorites were 22 and 21.5 $\mu g\ g^{-1}$ respectively [49]. The amount of each of the 8 aminoacids of the non-protein type was smaller than that of the protein aminoacids, with the exception of α-aminoisobutyric acid, the concentration of which was at the level of those of the protein aminoacids. A more detailed analysis of the Murray meteorite [55], carried out by the method used in the studies of Kvenvolden and coworkers [47,48], established that this meteorite contains at least 18 aminoacids. The ratios of the D- and L-isomers of some of them are analogous to the ratios in the Murchison meteorite (Fig. 2). It has recently been established by the same analytical techniques [56] that one of the oldest carbonaceous chondrites (the Orgueil chondrite which fell in France in 1864) also contains aminoacids, some of which are probably of non-biological origin, since they are present in the form of racemic mixtures (Table 2).

The Moon

The analyses of lunar rocks supplied by Soviet and American spaceships are of undoubted interest. The search for aminoacid precursors in these rocks revealed the presence of hydrocarbons, carbides, and other compounds. For example, the experiments of Abell et al. [57], who treated lunar dust with deuterated acids (a 38% solution of DCl in D_2O and a 20% solution of DF in D_2O), led to the discovery of methane and ethane as well as carbides. The specimens of lunar rocks brought by the Apollo 11 and 12 expeditions evolved hydrocarbons on treatment with hydrofluoric, orthophosphoric, or sulphuric acid, one of the main components of which was methane [58,59]. Grinding the lunar rocks in glass ball mills also resulted in the evolution of methane which was probably present in a free state as inclusions (gas bubbles) in the solid rock.

Lunar rocks obtained by the recent Apollo 16 and 17 expeditions contained approximately the same amount of

Table 2. Aminoacids obtained in non-biological syntheses and detected in meteorites and lunar rocks (the molar composition is given; for the lunar specimens, in 1×10^{-9} mole per gramme of rock).

No.	Aminoacid	Non-biological syntheses									Analysis of extraterrestrial specimens						
		in electric discharges				on u.v. irradiation	thermal				meteorites***				lunar rocks from Apollo expeditions		
		1*	2	3	4	5	6	7	8**	9	10	11	12	13	14	15	16
1	Alanine	27.4	+	+	+	+	16.9	20.2	10.0	5.0	+	+D, L	+D, L	+D, L	19	3	7
2	Arginine	—	—	—	—	+	—	—	1.2	—	+	—	—	—	—	—	—
3	Aspartic acid	0.3	+	+	+	—	2.5	15.2	12.5	1.3	+	+D, L	+D, L	+D, L	5	2	7
4	Valine	—	—	—	+	+	1.2	2.1	3.5	0.4	+	+L	+D, L	+D, L	<1	<1	—
5	Histidine	—	—	—	—	—	—	—	2.0	—	+						
6	Glycine	50.8	+	+	+	+	68.8	24.4	16.8	39.5	+	+	+	+	52	70	57
7	Glutamic acid	0.5	+	+	+	+	3.1	10.2	27.0	1.6	+		+D, L	+D, L	11	6	13
8	Isoleucine	—	+	+	—	+	0.7	2.5	3.7	9.4	+	—	—	—	<1	<1	1
9	Leucine	—	—	+	—	+	1.5	4.6	5.5	0.5	+	—	—	—	<1	<1	3
10	Lysine	—	—	—	—	+	—	—	1.9	—	+	—	—	—	—	—	—
11	Proline	—	—	—	+	—	1.5	2.3	7.4	5.0	+	+D, L	+D, L	+D, L	—	—	—
12	Serine	—	+	+	—	+	1.9	10.0	2.0	4.0	—	—	—	—	10	3	10
13	Tyrosine	—	—	—	—	+	0.4	2.0	0.8	—	+	—	—	—	—	2	—
14	Threonine	—	+	+	—	+	0.6	3.0	2.3	—	—	—	—	—	3	—	2
15	Phenylalanine	—	+	—	—	—	0.6	2.2	2.1	1.2	—	—	—	—	—	—	—
16	Isoserine	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
17	α-Aminoisobutyric acid	—	+	—	—	—	—	—	—	—	+	+	+	+	—	—	—
18	α-Amino-n-butyric acid	4.0	—	+	+	—	—	—	—	—	+	—	+D, L	+D, L	—	—	—
19	Sarcosine	4.0	—	+	+	—	—	—	—	—	+	+	+	+	—	—	—
20	β-Alanine	12.1	—	+	+	—	+	+	—	—	+	+	+	+	—	—	—
21	β-Aminoisobutyric acid	—	—	—	+	—	—	—	—	—	+	+D, L	+D, L	+D, L	—	—	—
22	β-Amino-n-butyric acid	—	—	—	+	—	—	—	—	—	—	+	+	+	—	—	—
23	γ-Aminobutyric acid	—	—	—	+	—	—	—	—	—	+	+	+	+	—	—	—
24	Isovaline	—	—	—	+	—	—	—	—	—	—	—	+D, L	+D, L	—	—	—
25	Norvaline	—	—	—	+	—	—	—	—	—	—	—	+	+	—	—	—
26	N-Methyl-β-alanine	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
27	N-Methylalanine	0.8	—	+	+	—	—	—	—	—	—	—	+	+	—	—	—
28	N-Ethyl-β-alanine	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
29	αβ-Diaminobutyric acid	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
30	N-Ethylglycine	—	—	—	+	—	—	—	—	—	—	—	+	+	—	—	—
31	αβ-Diaminopropionic acid	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
32	γ-Amino-α-hydroxy-butyric acid	—	—	—	+	—	—	—	—	—	—	—	+D, L	+D, L	—	—	—
33	Pipecolinic acid	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
34	Norleucine	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
35	Alloisoleucine	—	—	—	+	—	0.3	1.4	—	—	—	—	—	—	—	—	—
36	N-Propylglycine	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
37	N-Isopropylglycine	—	—	—	+	—	—	—	—	—	—	—	—	—	—	—	—
38	Ornithine	—	—	—	—	+	—	—	—	—	+	—	—	—	—	—	—

*1) Refs. 3 and 4; 2) Ref. 108; 3) Ref. 105; 4) Refs. 95 and 96; 5) Refs. 102 and 121–123; 6) and 7) Refs. 132 and 133; 8) Ref. 136; 9) Refs. 140 and 141; 10) Ref. 25; 11) Ref. 56; 12) Refs. 49 and 55; 13) Refs. 47 and 48; 14)–16) Ref. 69.

**Methionine was also detected (1.2%).

***+D, L denotes the presence of enantiomers.

total hydrogen as the specimens brought by the earlier expeditions—between 4 and 206 parts per million [60]. Aminoacid precursors were detected at the level of several parts per 1000 million. Nitrides, carbides, water, carbon dioxide, hydrogen, and various metals and their oxides were found in lunar materials [61]. Hopeful results have now been obtained, suggesting that these materials contain organic products, including aminoacids of non-biological origin. After extraction with cold water in two laboratories of the lunar rocks supplied by the astronauts of the Apollo 11 expedition, aminoacids were not detected [62,63]. All other groups of investigators extracted the specimens with hot water and did discover aminoacids [64–67]. The identification of glycine (32 μg per kg of lunar dust) and alanine (36 μg kg^{-1}) in aqueous non-hydrolysed extracts has been reported [64,67]. Fox and coworkers [65,66] used extraction with hot water followed by hydrolysis. Analysis on an ultrasensitive ion-exchange chromatograph detected glycine and alanine in the same amounts as those obtained by other investigators [64], but threonine, serine, and aspartic and glutamic acids were also found. It has been shown [64,66] that aminoacids are present in lunar rocks mainly as polymers.

A scheme for the complete analysis of organic substances of different classes in lunar materials supplied by the crew of the Apollo 11 spaceship has been described [58, 68,69] (Fig. 3). It was developed on the basis of numerous investigations of organic compounds in old rocks and meteorites. In this scheme, organic substances of different classes are extracted in succession from a single large specimen with minimal transfer of materials. Such consecutive tests of lunar specimens did not prove to be

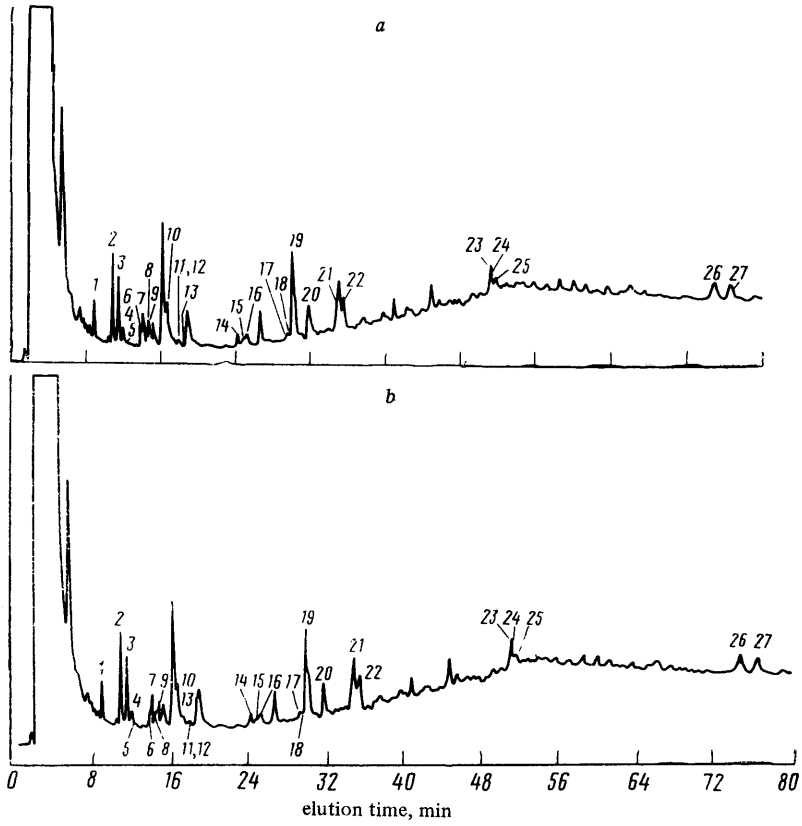


Figure 2. Chromatograms of the aminoacids from the Murchison (*a*) and Murray (*b*) meteorites: 1) isovaline; 2) α-aminoisobutyric acid; 3) D-valine; 4) L-valine; 5) *N*-methylalanine; 6) D-α-aminobutyric acid; 7) D-α-alanine; 8) L-α-aminobutyric acid; 9) L-α-alanine; 10) *N*-methylglycine; 11) *N*-ethylglycine; 12) D-norvaline; 13) L-norvaline; 14) D-β-aminoisobutyric acid; 15) L-β-aminoisobutyric acid; 16) β-aminobutyric acid; 17) D-pipecolinic acid; 18) L-pipecolinic acid; 19) glycine; 20) β-alanine; 21) D-proline; 22) L-proline; 23) γ-aminobutyric acid; 24) D-aspartic acid; 25) L-aspartic acid; 26) D-glutamic acid; 27) L-glutamic acid.

sufficiently effective and were not used in subsequent analyses. However, this unique scheme may be useful in the study of geological and extraterrestrial specimens available in limited amounts.

Yet another scheme has been proposed[70] for the analysis of organic substances in lunar specimens. Here it is suggested that a closed extraction apparatus be used, whereby one can carry out the extraction (with the aid of ultrasound), evaporation, separation on columns with adsorbents, and the collection of fractions in a closed system. Solvents and solutions are transferred from one apparatus to another by the pressure of pure helium. However, the nature of the carbon-containing compounds in lunar rock precluded the application of this scheme. Nevertheless, there is hope that this idea may prove useful in designing an apparatus for the remote investigation of the organic substances present on other planets.

The techniques used in the extraction and hydrolysis of the lunar specimens supplied by the Apollo 11 and 12 expeditions have been described in detail also in other reports[71-73], which likewise confirm that schemes in which provision is made for the isolation of any one class of compounds are the most rational.

Thus in the analysis of the first lunar specimens use was made of three methods involving extraction by aqueous and non-aqueous solvents: boiling in open and closed systems, Soxhlet extraction, and extraction with the aid of ultrasound[59]. It has been shown that aminoacids and their precursors may be most effectively sought by extraction with hot water followed by acid hydrolysis of the aqueous extract[65]. Extraction with non-aqueous solvents and direct acid hydrolysis of the lunar specimens do not yield positive results[59,62,63]. Direct hydrolysis of the lunar specimen with 6 *N* HCl is accompanied by the formation of a very large amount of salts, which greatly impair the extraction process. It may be that treatment of lunar rocks with hot hydrochloric acid leads to the decomposition of aminoacids[59,74]. Extraction with water

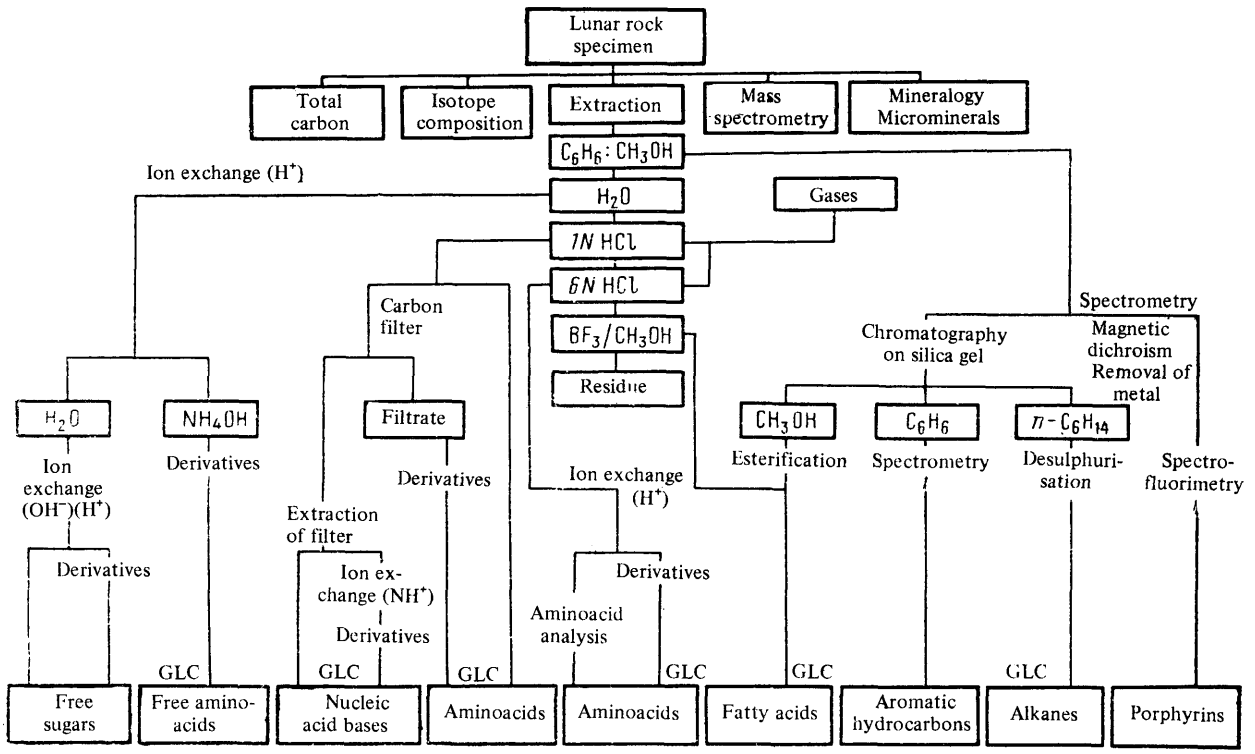


Figure 3. A scheme for the complete analysis of organic compounds in lunar rocks[65].

followed by the hydrolysis of the extract (indirect hydrolytic scheme) has been rapidly adopted and used to search for aminoacids in other specimens of lunar rocks and in meteorites.

Together with a detailed description of the analytical technique for lunar rocks provided by the Apollo 11, 12, and 14 expeditions, the paper by Fox et al.[34] presents also the qualitative and quantitative compositions of the aminoacids detected in such rocks (Table 2). The results in Table 2 show that the same aminoacids were identified in almost all instances.

Analysis of lunar specimens revealed the presence of aminoacids in very small amounts (20–70 parts per 1000 million)[44,65]. It was therefore of interest to test for the presence in these specimens of biological contaminations of terrestrial origin. Comparison of the analytical results for lunar specimens on an ultrasensitive aminoacid analyser with the aminoacid content in fingerprints suggests the absence of such contaminations (Fig. 4).[44] A blank experiment demonstrated the absence of aminoacids from the reagents employed.

The possibility that the aminoacids detected might have been formed on oxidation of the rocket fuel (1,1-dimethylhydrazine) on the surface of the Moon was tested directly on a lunar specimen[75]. The specimen was taken from beneath the lunar module of the Apollo 15 expedition after it had been acted upon by the exhaust gases of the engine of the descent apparatus. The results of the analysis of the hydrolysates of this specimen revealed a lower overall amount of aminoacids than in the specimens investigated previously[34,75]. Their qualitative composition proved to be the same. It follows from this that the rocket fuel oxidation products do not contaminate lunar soil with aminoacids. It is possible that the hot exhaust gases actually decompose the lunar aminoacids. Furthermore, oxidation of 1,1-dimethylhydrazine under laboratory conditions does not lead to the synthesis of aminoacids[66].

The study of the isotope composition of lunar carbon also indicates the absence of terrestrial contaminations. The isotope composition of the carbon in lunar rocks, collected in the Sea of Tranquility, varies from +2.2 to +10.8‰ (breccia) and from +15 to +20‰ (lunar powder)[62,76,77]. The distribution of carbon isotopes in the lunar powder specimens supplied by the Apollo 16 expedition varied from +9.4 to +16.1‰ for a total amount of carbon of 88–206 parts per million[61]. Thus, one may assume that lunar carbon is anomalously heavier compared with terrestrial carbon (Fig. 1).

The analytical data show that the aminoacids in lunar rocks are present in a bound form and are not terrestrial contaminations or rocket fuel combustion products. The low concentration of aminoacids suggests that they might have appeared on the Moon as a result of the incidence of organic compounds from interstellar matter[78], comets' tails[79], solar wind[60], and meteorites[48]. Interstellar matter probably makes the smallest contribution to the formation of aminoacids on the Moon's surface[80] and solar wind the highest.

The Planets

Data concerning the composition of the atmospheres of the planets in the solar system are very important for the determination of aminoacid precursors (Table 3). Table 3 shows that Earth differs strongly from the other planets

in the composition of the atmosphere, which is probably due to the presence of life on Earth. The exact composition of the primary terrestrial atmosphere is unknown. Oparin assumed that Earth was formed by a cold process and its atmosphere might therefore have contained hydrogen, methane, and the inert gases[1]. This reducing atmosphere was gradually enriched in the gases evolved from the Earth's core—methane, hydrogen sulphide, and ammonia. It probably also contained water vapour. An atmosphere having this composition might have served as a source of various organic substances on Earth. Numerous subsequent experiments confirmed the possibility of the synthesis of aminoacids under the reducing conditions of the primary terrestrial atmosphere. Experiments simulating Jupiter's atmosphere[82] also demonstrated the possibility of the synthesis of organic compounds which are precursors of biologically important molecules.

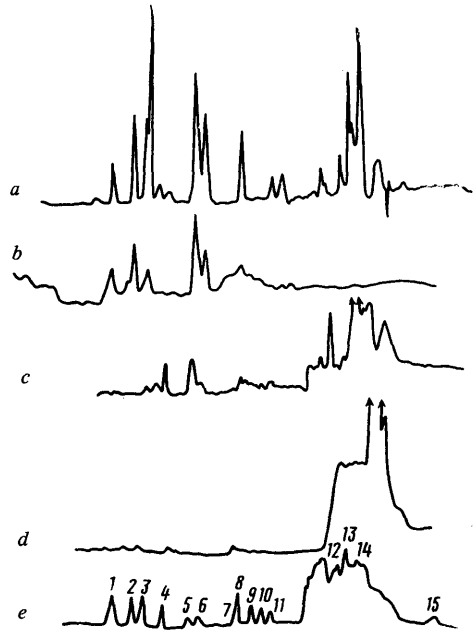


Figure 4. Chromatograms of aminoacid mixtures obtained in separation on an ion-exchange analyser[44]: *a*) contaminations by human fingerprints; *b*) hydrolysate of the aqueous extract of lunar dust (Apollo 11); ditto (Apollo 12); *d*) aqueous solutions in a blank experiment; *e*) mixture of standard aminoacids [1) aspartic acid; 2) threonine; 3) serine; 4) glutamic acid; 5) glycine; 6) alanine; 7) cysteine; 8) valine; 9) methionine; 10) isoleucine; 11) leucine; 12) histidine; 13) lysine; 14) ammonia; 15) arginine].

Some investigators believe that the atmosphere of the primitive Earth was not entirely reducing[83]. The primitive atmosphere might have been formed from the gases evolved from the Earth's mantle and core. Methane, carbon dioxide, and a number of radicals (C_2, C_3, CH_3, CN, etc.) are formed at present in the Earth's mantle and were probably formed during the cooling of the fused Earth[84,85]. The primary atmosphere might have been close in composition to that of volcanic gases. The gases which are ejected by volcanoes at the present time contain largely CO_2, CO, CH_4, H_2, N_2, and possibly HCN.[86-88] In 1973 Soviet investigators succeeded in confirming that volcanic gases contain hydrogen cyanide—a most important aminoacid precursor[89]. Its concentration in the gases evolved by the incandescent lava (at 900°C) of the volcano Alaid in the Kuril islands is about 0.01 mg litre^{-1}. Aminoacids and their precursors have been obtained from gases having a composition close to that of volcanic gases (see the next Section). The data presented show that, during certain periods of evolution, the atmosphere of the primitive Earth might have had a composition resembling that of the atmospheres of Jupiter and Saturn (the "fossil" planets) or Venus and Mars.

Table 3. The compositions of the atmospheres of the planets in the solar system[13,81] (the components are listed in order of decreasing concentrations).

Planet	Components
Venus	CO_2,CO, HCl, HF, H_2O (O_3?), (N_2?)
Earth	N_2, O_2, H_2O, Ar, CO_2, Ne, He, CH_4, Kr, N_2O, H_2, O, O_3, Xe
Mars	CO_2, CO, H_2O, O_2, (CH_4?), (NH_3?), (N_2?)
Jupiter	H_2, CH_4, NH_3
Saturn	H_2, CH_4, (NH_3?)
Uranus	H_2, CH_4
Neptune	H_2, CH_4

When an oxidising atmosphere is simulated (a mixture of CO_2, H_2O, N_2, and O_2), it is impossible to synthesise important aminoacid precursors such as HCN, CH_3CHO, CH_3NH_2, etc.[90] Thermodynamic calculations have shown that, under the conditions of a reducing atmosphere (a mixture of NH_3, H_2, H_2O, and CH_4), the enthalpies of formation of these compounds are an order of magnitude lower than in an oxidising atmosphere.

The principal ways in which the most important aminoacid precursors (methane, hydrogen cyanide, cyanoacetylene, the simplest aldehydes, and others) are synthesised have been thoroughly examined[5,8,9]. For example, it is known that hydrocarbons may be formed at an elevated temperature from carbon and hydrogen, a mixture of carbon monoxide or dioxide with hydrogen, and also when metal carbides are acted upon by water. Hydrogen cyanide is obtained in electric discharges between carbon electrodes in an atmosphere of nitrogen and hydrogen, nitrogen and methane, or carbon monoxide and hydrogen. Under the same conditions, cyanoacetylene may be formed. Lower aldehydes may be synthesised by the action of ultraviolet radiation or an electric discharge on CO_2–H_2O, CO–H_2O, CH_4–H_2O, and even CO–H_2 mixtures.

Thus the most varied primary compounds, which are of interest as aminoacid precursors, might have existed in the atmosphere or hydrosphere of the primitive Earth. To some extent, they might have been brought to Earth from space in one way or another or they might have arisen spontaneously from the simplest organic and inorganic substances present on Earth itself. During chemical evolution, these compounds, particularly methane, ammonia, water, formaldehyde, and hydrogen cyanide, served as the starting materials in the non-biological syntheses of various biologically important substances, particularly aminoacids.

III. PREBIOLOGICAL SYNTHESIS OF AMINOACIDS

The majority of the syntheses of aminoacids require the expenditure of energy. Under the conditions of the primitive Earth, the following different energy sources might have existed: ultraviolet radiation from the Sun—570.0 cal cm^{-2} per year ($\lambda < 250$ nm); electric discharges (atmospheric lightning)—3.9 cal cm^{-2} per year; radioactive emission from the Earth's core (at depths down to 1 kilometer)—0.8 cal cm^{-2} per year; volcanic heat (as a result of magmatic activity)—0.13 cal cm^{-2} per year; cosmic rays—0.0015 cal cm^{-2} per year [91].

a. Synthesis in Electric Discharges

Aminoacids were obtained for the first time under laboratory conditions by Miller [3,4,92] when a mixture of gases simulating the atmosphere of the primitive Earth were subjected to the action of electric discharges. Miller's apparatus consisted of a 5-litre flask (fitted with two electrodes), through which a mixture of water vapour, methane, ammonia, and hydrogen circulated. A potential of 60 kV was applied to the electrodes and the arc was struck.

After incubation for a week, it was found that HCN, HCHO, CH_3CHO, aminoacids, hydroxyacids, carboxylic acids (Table 2) urea, and *N*-methylurea had been synthesised. Altogether 11 aminoacids were found, glycine, α-alanine, β-alanine, and α-aminobutyric acids being obtained in amounts sufficient for identification on the basis of the melting points of their derivatives.

Miller [34,92] suggested two possible pathways to the synthesis of aminoacids: (1) their generation in the gas phase from the radicals and ions formed in the electric discharges from mixtures of methane, ammonia, and water; (2) the formation in the gas phase of only the simplest aldehydes and nitriles, which are then converted into aminoacids in the liquid phase. The secondary pathway appears to be more likely. Analysis of the gas phase reveals the presence of HCN, HCHO, and CH_3CHO, their amount increasing to a maximum at the beginning of the reaction and then falling. These observations enabled Miller to suggest the occurrence of the Strecker reaction in the synthesis of aminoacids and hydroxyacids in the liquid phase. Aminonitriles should have been formed as intermediates:

$$R{-}CHO + NH_3 + HCN \rightarrow \underset{\displaystyle NH_2}{\overset{\displaystyle |}{R{-}CH{-}CN}} \xrightarrow[2H_2O]{-NH_3} \underset{\displaystyle NH_2}{\overset{\displaystyle |}{R{-}CH{-}COOH}}\,.$$

To confirm the proposed mechanism, Miller carried out the alkaline hydrolysis of a synthetic mixture of RCHO, HCN, and NH_3. This also yielded glycine, α-alanine, and α-aminobutyric acid. The last two aminoacids were obtained in much greater amounts than in the experiment with an electric discharge. An important confirmation of this mechanism is provided by the detection in the liquid phase of the corresponding hydroxyacids (glycolic, lactic, and α-hydroxybutyric) in approximately equal proportions together with the aminoacids (glycine, α-alanine, and α-aminobutyric acid). This finding suggests that the acids are synthesised simultaneously with equal thermodynamic and kinetic probabilities. The detection of a large amount of formic acid also confirms the importance of the role of hydrocyanic acid as an intermediate in prebiological synthesis.

Some workers believe [86,93,94] that the content of ammonia in the primitive atmosphere of Earth was not more than 10^{-5} atm. This does not, however, diminish the important role which ammonia might have played in the prebiological synthesis of organic compounds in the ocean. In their latest studies Miller and coworkers [95,96] investigated in detail the synthesis of aminoacids in electric discharges in mixtures of methane, nitrogen, and water containing traces of ammonia. They detected 28 aminoacids by ion-exchange chromatography and gas chromatography combined with mass spectrometry (Table 2). Their overall yield was 15.5% (with respect to carbon).

It is noteworthy that previously many investigators found a wide variety of protein and non-protein aminoacids in analogous syntheses. However, the reliable detection in a single experiment of 20–30 aminoacids at once, when these are present in very small amounts, became possible only recently as a result of the great sophistication of analytical techniques.

It has been suggested [96] that, when a mixture of methane, nitrogen, and water is subjected to the action of electric discharges, aminoacids are formed mainly via nitriles and aminonitriles. The high content of hydrocyanic acid in the aqueous phase and the fact that the presence of γ-amino-α-hydroxybutyric, $\alpha\gamma$-diaminobutyric, and $\alpha\beta$-diaminopropionic acids and serine is associated with nitrile precursors support this hypothesis. The absence of ammonia from the initial mixture probably rules out the Strecker synthesis in the present instance.

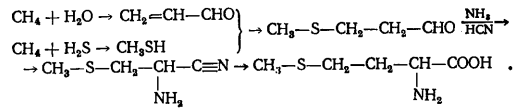
According to Miller, aspartic and glutamic acids are formed by the Strecker reaction via α-cyanoacetaldehyde and β-cyanopropionaldehyde. This is confirmed by the detection in the electric discharges of cyanoacetylene [97], which may be regarded as a precursor of cyanoacetaldehyde.

The mechanism of the synthesis of aspartic acid via diacetylene, which is always present in the gases formed by the electrocracking of hydrocarbons, also appears to be likely [98,99]. At elevated temperatures diacetylene may combine with two ammonia molecules with formation of succinodinitrile. Radical amination of the latter and hydrolysis of the aminodinitrile lead to aspartic acid. Glutamic acid can also be synthesised from diacetylene by the addition of ammonia and water with intermediate formation of β-cyanopropionaldehyde.

By subjecting various hydrocarbons to high temperatures or electric discharges, it is possible to synthesise phenylacetylene [100], which is readily hydrated to phenylacetaldehyde. The yield of the aldehyde increases when the reaction proceeds via the nucleophilic or radical addition of hydrogen sulphide followed by the hydrolysis of the thioaldehyde [101]. Next ammonia and hydrogen cyanide add on by the Strecker reaction with formation of the nitrile of phenylalanine and then of phenylalanine itself. In the radical addition of hydrogen sulphide to phenylacetylene, a low yield of tyrosine was obtained. The above sequence of reactions probably determines the mechanism of the synthesis of these aminoacids in the presence of hydrogen sulphide. However, previously investigators [102,103] detected phenylalanine in mixtures synthesised non-biologically in the absence of hydrogen sulphide.

The prebiological synthesis of methionine has been achieved [104] by exposing a mixture of methane, nitrogen, ammonia, water, and hydrogen sulphide (or thiomethanol) to an electric discharge. It is believed that acrolein,

which has been detected in the resulting mixture, is an intermediate in this reaction:



The authors note that acrolein may be a precursor not only of methionine, but also of homocysteine, glutamic acid, homoserine, and $\alpha\gamma$-diaminobutyric acid. This is possible when hydrogen sulphide, hydrogen cyanide, water, or ammonia add to its double bond.

Experiments[105] analogous to the first experiment carried out by Miller revealed an acceleration of the synthesis of aminoacids. Exposure to electric discharges for the first 20 h led to the formation of two aminoacids, four aminoacids were detected after 100 h, and 12 aminoacids after 200 h. Abelson[106] subjected to the action of electric discharges mixtures of gases with different concentrations of H_2, CH_4, CO_2, CO, H_2O, NH_3, N_2, and O_2. He demonstrated that aminoacids are synthesised only in a reducing atmosphere (oxygen inhibits their formation) and emphasised the role of hydrogen cyanide as an intermediate in these syntheses.

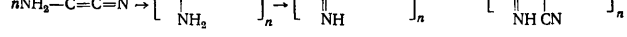
Pavlovskaya and Pasynskii[107] obtained the same set of aminoacids as Miller[3,4] when they exposed to spark discharges a different mixture, which, however, was of a reducing type (CH_4, NH_3, CO, and H_2O). A thermodynamic assessment of the pathway followed in this synthesis showed that aminoacids are formed with a decrease of free energy ($\Delta G_0 = -5.9$ kcal mole^{-1}), while in Miller's model mixtures the free energy increases ($\Delta G_0 = +62$ kcal mole^{-1}), i.e. the conditions are less favourable. The main conclusion reached in this important study involves the hypothesis that the loss of hydrogen from the terrestrial atmosphere could not have been a major obstacle to the synthesis of aminoacids.

Electric discharges have also been used to treat mixtures of methane, ammonia, and water vapour[108]; 45% of the products formed were found in the aqueous phase where the concentration of hydrocyanic acid was highest. After the hydrolysis of the aqueous phase (6 *N* HCl, 100°C, 24 h), glycine, alanine, aspartic and glutamic acids, threonine, serine, isoleucine, and phenylalanine were found by ion-exchange and gas chromatography. Hydrolysis of the polypeptides, detected in the reaction mixture, yielded the same aminoacids. In the reaction mixture, aminoacids are present in a free state only in trace amounts. It was concluded that, in the presence of a condensing agent (cyanamide), the aminoacids synthesised are converted into polypeptides in the aqueous phase.

Ponnamperuma and Woeller[109], who subjected an anhydrous equimolecular mixture of methane and ammonia to the action of spark discharges (4 kV, 0.5 mA), demonstrated the formation of nitriles and aminonitriles in the gas phase in the absence of aldehydes, which are necessary for Strecker condensations. Only the simplest aminonitriles (aminoacetonitrile and aminopropionitrile) were detected in the reaction gases. After the hydrolysis and esterification of the involatile liquid fraction in an analogous experiment[110], glycine, alanine, sarcosine, β-aminoisobutyric acid, diethylaminomalonic acid, etc. were detected.

These experiments indicate a different mechanism for the formation of aminonitriles—the direct precursors of aminoacids. At the high temperatures of the electric discharge, there is an equilibrium system consisting of molecular acetylene, hydrogen, and many radicals: C_2H, CH, CH_2, CH_3, NH, NH_2, CN, H, etc. When the temperature is reduced, the radicals recombine with formation of molecular compounds: acetylene and its homologues, hydrogen cyanide, cyanoacetylene, nitriles, and aminonitriles. Hydrolysis of the aminonitriles formed in this way yields the corresponding aminoacids.

Having determined the molecular weights of the liquid fractions obtained in similar experiments, Ponnamperuma and coworkers[109-111] concluded that the heavy fractions consist mainly of polymers (M from 2.4×10^2 to 1.4×10^3). The synthesis of these polymers can be accounted for on the basis of polymerisation of hydrogen cyanide[112-114], which is formed in the electric discharges from methane and ammonia. In the gas phase, hydrogen cyanide dimerises spontaneously in the presence of ammonia, forming the aminocyanomethylene biradical $H_2N-\dot{C}=C=\dot{N}$.[115,116] The latter polymerises rapidly and the resulting polymer tautomerises to polyiminoketimine, which interacts with hydrogen cyanide to form polyiminomalononitrile:



Hydrolysis of such compounds can lead to the formation of polypeptide chains, which are subsequently decomposed to aminoacids. In this mechanism, hydrogen cyanide is the main precursor of aminoacids, giving rise in an anhydrous gaseous phase to a number of nitriles and imino- and amino-compounds, which are starting materials for the synthesis of aminoacids and polypeptides.

The experiments of Toupance et al.[90] also emphasised the role of the nitrile group in the syntheses of aminoacid precursors from methane–ammonia mixtures in electric discharges (200 V, 100 mA). The infrared spectra (712 cm^{-1}) of the reaction mixture revealed a rapid increase of the concentration of hydrogen cyanide during the first seconds of the experiment. Subsequently its concentration remained unchanged.

Thus the following three pathways to the synthesis of aminoacids are possible under the influence of electric discharges through gases simulating the reducing atmosphere of the primitive Earth: (1) via aldehydes (with subsequent Strecker condensation); (2) via aminonitriles; (3) via nitrogen-containing polymers. It is extremely likely that non-biological synthesis included simultaneously all three mechanisms, particularly since in virtually all of them the principal role is assigned to acetylene and nitrile groups.

b. The Influence of Ultraviolet Radiation

Ultraviolet light has also been used to synthesise aminoacids. Groth and Weyssenhof[117] irradiated for a week with ultraviolet light from a low-pressure mercury lamp (4×10^{18} photons s^{-1}) a mixture of ammonia, methane, and water containing mercury vapour as the sensitiser. However, aminoacids were not detected in the subsequent analysis of the reaction mixture by paper chromatography. In this instance there was probably no direct photolysis of methane in the given wavelength ranges of the radiation and the probability of photosensitisation was low. The radicals and atoms obtained on photolysis or photosensitisation of ammonia (NH_2 + H) are

energetically relatively unreactive towards methane at the experimental temperature (50°C). Their reactivity begins to be manifested above 300°C. However, the replacement of CH_4 by C_2H_6 in this experiment led to the formation of aminoacids (the yields are indicated in brackets): glycine (32×10^{-6} M), α-alanine (23×10^{-6} M), and α-aminobutyric acid (0.5×10^{-6} M) as well as carboxylic acids: formic (72×10^{-6} M), acetic (203×10^{-6} M), and propionic (17×10^{-6} M). In the absence of a photosensitiser, the amount of aminoacids synthesised was lower.

When a methane-containing mixture was subjected to the shorter-wavelength radiation of the xenon lamp (147 nm and 129.5 nm, 4×10^{16} photons s^{-1}), aminoacids were also synthesised. In this case very small amounts of glycine and α-alanine were detected. Terenin and coworkers[118,119] achieved the photochemical synthesis of aminoacids from gaseous and liquefied mixtures of methane, ammonia, carbon monoxide, and water. They used a powerful hydrogen lamp whose radiation in the short-wavelength range ($\lambda \geqslant 130$ nm) was closer to the ultraviolet spectrum of the Sun. α-Alanine, α-aminobutyric acid, valine, and norleucine were detected in the synthesis products. Thus, short-wavelength radiation might have been sufficiently effective in the photolysis of mixtures of ammonia, methane, hydrogen, and water. This conclusion was confirmed by their ionisation potentials and quantum yields[120].

The photochemical synthesis of aminoacids from aldehydes and ammonium salts was developed in greatest detail by Pavlovskaya and coworkers[102,121-123]. Aqueous solutions of formaldehyde and ammonium nitrate were irradiated with ultraviolet light at a wavelength of 253.7 nm and 40°C in the course of 20–355 h. The aminoacid fractions, obtained by separation on ion-exchange resins, were analysed by paper and thin-layer (silica gel) chromatography. Serine, glycine, alanine, threonine, and basic aminoacids were detected. The qualitative and quantitative composition of the aminoacids changes somewhat following the irradiation of the initial solutions in the presence of natural adsorbents and catalysts: kaolinite, bentonite, limonite, and quartz. Numerous aminoacids are formed when acetaldehyde is irradiated instead of formaldehyde. In this case lysine, ornithine, arginine, glutamic acid, tyrosine, valine, leucine, and isoleucine were also found (Table 2).

The mechanism of the synthesis of aminoacids when gaseous mixtures of methane, ammonia, and other components are acted upon by ultraviolet radiation has been less thoroughly investigated. Presumably photolysis results in the formation of radicals analogous to those examined previously. For example, the photodissociation of methane does not stop at the stage involving the formation of the CH_3 radical, but very probably proceeds further to CH_2 and CH.[124] The quantum yield of ammonia reactions such as $NH_3 \rightarrow NH + H_2$ and $NH_3 \rightarrow N + H_2 + H$ increases with decrease of wavelength[125]. The recombination of various radicals can lead to the formation of aminonitriles.

Sidorov[126] and Pavlovskaya and coworkers[123] proposed a mechanism for the synthesis of aminoacids from aldehydes and ammonium salts under the influence of ultraviolet radiation. In the presence of formaldehyde, the $CH\dot{O}$ radical is formed initially, its recombination giving rise to glyoxal. The latter is converted under the influence of a light quantum into glyoxalic acid, which in the presence of ammonia and hydrogen gives rise to the simplest aminoacid—glycine. In the presence of higher aldehydes, other intermediate products are possible (ketoacids), which are transformed into more complex aminoacids.

The non-biologically synthesised aminoacids can themselves undergo interconversions. Thus, when valine is irradiated with ultraviolet light in the presence of metal oxides (ZnO and V_2O_5), glycine, threonine, and alanine are formed[127]. Alanine and glycine have been obtained from leucine under these conditions. In aqueous aminoacid solutions without metal oxides, new aminoacids are not formed. It is interesting that in the presence of MoO_3 irradiation of alanine or leucine leads to the formation of more complex aminoacids, for example, aspartic acid[128]. However, such acids are not formed from glycine. The photolysis of phenylalanine in the presence of polyphosphoric acid leads to its decomposition and hydroxylation, which results in the formation of tyrosine, alanine, and glycine[129]. In addition to the new aminoacids, ammonia, aldehydes, and carboxylic acids are formed under the conditions of the experiments.

c. Thermal Syntheses

The heat necessary for chemical synthesis on Earth might have been provided by early volcanic activity, which was probably much greater than at the present time. The wide distribution of regions in which thermal waters emerge on the surface suggests that the heat derived from thermal sources might have been important for the formation of aminoacids.

In order to investigate the possibility of the formation of biologically important compounds from gases evolved by magmatic rocks, Harada and Fox[130] heat-treated a mixture of methane, ammonia, and water. The initial gaseous products were passed at a high rate through a quartz tube heated to 900–1000°C. The tube was filled with silica gel, alumina gel, or volcanic lava. The reaction products were absorbed with aqueous ammonia and then hydrolysed (4 *N* HCl). Aminoacid analysis demonstrated the formation of a large proportion of protein aminoacids, including aromatic aminoacids, namely, aspartic and glutamic acids, threonine, serine, proline, glycine, alanine, valine, leucine, isoleucine, tyrosine, and phenylalanine. β-Alanine and certain other non-natural aminoacids were also detected.

This experiment aroused interest among investigators and was frequently repeated for a detailed investigation of the conditions of the synthesis and the composition of the aminoacids. Thus, Taube et al.[131] largely confirmed the results of Harada and Fox. Apart from the compounds indicated above, they identified lysine in the reaction mixture by electrophoresis. Oró[132,133], who carried out a similar experiment in the absence of a catalyst, showed that the same set of aminoacids is formed. Glycine and alanine had the highest concentrations in the mixture (Table 2). The reaction mixtures obtained under the conditions of the experiments of Harada and Fox[130] were recently analysed[134] by gas chromatography and mass spectrometry. It was shown that aminoacids are formed in low yields (0.007%) and fewer were found than in the experiment of Harada and Fox[130]. The authors note that β-aminoacids predominate in the mixtures.

Comparison of the experiments with the effect of electric discharges and heat on gaseous mixtures showed that the simplest aminoacids (glycine and alanine) are formed in maximum amounts regardless of the type of energy used.

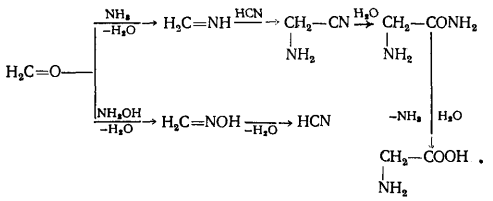
Aspartic and glutamic acids have been obtained in high yields by the thermal method. Reactions involving the isomerisation of the hydrocarbon chain (valine, leucine, and isoleucine are present in the mixture), cyclisation (tyrosine, phenylalanine, and proline), and hydroxylation (threonine, serine, and tyrosine) are more characteristic of thermopyrolysis. An increase of temperature favours these reactions [132,133]. Reactions involving the formation of unbranched chains (aminobutyric acid, sarcosine, and methylalanine) are more probable in electropyrolysis. It is noteworthy that the action of heat leads to the formation of mainly natural aminoacids.

It has been established that non-biological synthesis takes place at the present time and might have occurred in the remote past in the film on the edge of thermal sources and in the eruption of volcanoes [85,135]. Fox [136] analysed lava specimens collected with sterile steel rods in the eruption of Mauna Loa volcano (Hawaian Islands). The lava temperature during sampling exceeded 1000°C. The specimens were treated with hot water and the aqueous extract was hydrolysed (6 *N* HCl). Aminoacid analysis revealed the presence of 16 aminoacids (Table 2) with an overall yield of about 30×10^{-9} mole/g of lava. Glutamic (27%) and aspartic (12.5%) acids as well as glycine and alanine (16.8 and 10.0% respectively) were present in largest amount. It is interesting that a sulphur-containing aminoacid (methionine) was also detected in the mixture. The cooled lava had a bubble structure and consequently contained gas. Fox believes that the aminoacids were synthesised from the gases during their cooling.

Non-biological aminoacid mixtures can be obtained from CO, H_2, and NH_3 under the conditions of a modified Fischer–Tropsch process [25,137–139]. The initial mixtures of gaseous products were heated to 150–700°C in the presence of a wide variety of catalysts (montmorillonite, alumina gel, or silica gel). The resulting mixture contained a large proportion of protein aminoacids, including structurally complex aromatic and heterocylic aminoacids (Table 2), the yield of which was 0.01–0.1%.

Bakh was one of the first to use formaldehyde and hydrocyanic acid in thermal synthesis of non-biological aminoacids and polypeptides [9]. By heating (80–100°C) aqueous mixtures of hydrocyanic acid and ammonia or formaldehyde and hydroxylamine, it is possible to obtain the following aminoacids [133]: glycine, alanine, aspartic and glutamic acids, serine, threonine, leucine, isoleucine, arginine, α-amino-n-butyric and $\alpha\beta$-diaminopropionic acids, and β-alanine. In the latter mixture, a considerable amount of glycine is formed. When hydroxylamine is replaced by hydrazine, certain aminoacids are again synthesised. Simple heating of an aqueous solution of formaldehyde with ammonia (3 : 1) followed by acid hydrolysis (185°C, 8 h) led to the formation of a mixture of aminoacids [140,141], which qualitatively differed little from the mixture obtained by Pavlovskaya and coworkers [121,122]. The quantitative proportions of the aminoacids are indicated in Table 2. Their overall yield was 0.007%. Hexamethylenetetramine was detected in the reaction product. The reaction has also been achieved in the presence of lunar dust [136]. After hydrolysis, six aminoacids were detected, the amounts of glycine and glutamic acid being greatest.

The synthesis of aminoacids on heating formaldehyde and ammonia [140,141] proceeds via hexamethylenetetramine [142], the formation of which from these starting materials was first demonstrated by Butlerow [43]. The acid hydrolysis of hexamethylenetetramine also yielded all the aminoacids synthesised from CH_2O and NH_3. [142] Oró [144] suggests that aminoacids are formed in thermal syntheses from a mixture of formaldehyde, hydroxylamine, and water via oximes, hydrocyanic acid, and aminoacid amides. For example, the following reaction mechanism is possible in the case of glycine:



The high reactivities of aminonitriles, which are important aminoacid precursors, has been noted in the literature. Thus Moser and Matthews [145] reported that certain α-aminoacids are formed on neutral or alkaline hydrolysis of aminoacetonitrile. They believe that aminoacids are synthesised via the decomposition of aminoacetonitrile to HCN and NH_3, the polymerisation of HCN, and subsequent hydrolysis of the polymer to various aminoacids.

In the presence of CH_2O, aminoacetonitrile can give rise to methyleneaminoacetonitrile, which is also readily formed from CH_2O, HCN, and NH_4OH. [146] This compound is converted on mild hydrolysis (110°, pH 5.5–10) into glycine, serine, hydroxymethylserine, alanine, sarcosine, and di- and tri-glycine. It has been suggested that glycine and formaldehyde are the products of the direct hydrolysis of methyleneaminonitrile, while serine and hydroxymethylserine are obtained on *C*-hydroxymethylation of the reactive methylene group of the initial compound (or of the glycine formed) by formaldehyde. Alanine is probably formed from serine via dehydroalanine.

In order to elucidate the mechanism of the synthesis of complex aminoacids, it is quite justifiable to attempt to use as starting materials the simplest aminoacids or their derivatives, which are obtained in high yields in most non-biological syntheses. Thus, the synthesis of valine and isoleucine, aminoacids with branched hydrocarbon chains, is probably based on the fairly high yield of the nitrile of glycine formed on cyanide polymerisation [112]. The nitrile gives rise to the required aminoacids in the presence of acetone or ethyl methyl ketone (40°C, 21 days) [147]. The yield of valine is 0.3% and that of isoleucine is lower by an order of magnitude. Ketones are believed to be the products of non-biological syntheses, since they can be obtained from the corresponding acetylene homologues.

The possibility of the formation of serine by the reaction of glycine with formaldehyde (60–100°C, phosphate buffer) has been demonstrated [147]. It was shown that formaldehyde exhibits catalytic activity. Apart from serine, hydroxymethylserine, sarcosine, alanine, and iminodiacetic acid may be obtained from dilute alkaline solutions of glycine and formaldehyde [148]. The introduction of acetaldehyde or benzaldehyde leads to the synthesis of threonine or β-phenylserine respectively.

The most complex aminoacid (tryptophan) was obtained by the Michael reaction (60–100°C, 8–53 days) from indole and dehydroalanine employed in the form of a peptide to increase its stability [147]. The yield of tryptophan was between 0.01 and 0.5%. Indole, formed in small amounts in electric discharges from hydrocarbons and ammonia, can also be regarded as a precursor of tryptophan.

d. Other Syntheses

There have been fewer studies in which prebiological syntheses of aminoacids under the influence of ionising radiation were investigated. However, they confirm to a large extent the results obtained by the procedures discussed above. Palm and Calvin [149] irradiated with fast electrons in a linear accelerator (5 MeV, overall dose 10^9 rad, 6 ms pulses at a frequency of 30 Hz) a gaseous mixture of CH_4, NH_3, and H_2O, which was kept over an ammonia solution of magnesium and iron silicate or ammonium phosphate; the experimental temperature was 30–80°C. Analysis of the liquid phase by ion-exchange and paper chromatography demonstrated the formation of a multiplicity of products: aminoacids (glycine, alanine, and aspartic acid), hydrocyanic and lactic acids, urea, C_3–C_6 sugars, etc. Unfortunately, the gas phase was not analysed.

Studies by Oró [133] confirmed and extended these experiments. A similar mixture was irradiated under identical conditions and the same aminoacids were detected by paper radiochromatography. In addition, glycine amide was identified. Oró also reported a novel method for irradiating with fast electrons a solid mixture of CH_4, NH_3, and H_2O at the liquid nitrogen temperature. The aim of the experiment was to simulate the irradiation of the nucleus of a comet in space. Similar aminoacids were detected in the aqueous phase [149], but their radiochemical yields could not be found owing to the lack of analytical data for the gaseous phase.

Choughuley and Lemmon [150] demonstrated the possibility of synthesising sulphur-containing aminoacids on irradiation of a mixture of CH_4, NH_3, H_2O, and H_2S with fast electrons. Nevertheless, it was difficult to obtain them in satisfactory yields under such conditions owing to the ease of oxidation of the mercapto-groups by the water radiolysis products.

Studies on the synthesis of aminoacids from a mixture of gases (CH_4, NH_3, H_2O, N_2, and CO_2) under the influence of low-intensity X-rays have been carried out [151]. Electrophoretic analysis of the aqueous extracts of the radiolysis products demonstrated the formation of neutral and acid aminoacids as well as amines. In subsequent similar investigations [152], glycine, alanine, and aspartic acid were found. The radiochemical yields of the aminoacids were low owing to the low selectivity of the process. Furthermore, one may note that the radioactivity might possibly have supplied energy for the synthesis of aminoacids mainly on the surface of the primitive Earth and not in the atmosphere.

Aminoacids can also be obtained in the field of ultrasonic waves [153]. Aqueous solutions of organic acids, formed by the Miller electrosynthesis [3], saturated with molecular nitrogen or a nitrogen–hydrogen mixture served as the starting materials. The formation of aminoacids was also observed following the exposure of ammonium chloride solutions containing urea or hydroxylamine to ultrasound. Experiments have been carried out recently using the energy of a shockwave [154–156]. Similar conditions are likely to have occurred on collision of meteorites with Earth's atmosphere. A number of aminoacids obtained from the gaseous mixture were identified in these experiments.

The aim of the studies considered in this section was to investigate mainly the possibility of the prebiological synthesis of protein aminoacids, i.e. to investigate one of the first steps in chemical evolution on Earth. Considerable advances have been made in this field. Almost all the protein aminoacids and a series of non-protein aminoacids have been synthesised. It is interesting that, regardless of the type of energy employed, various methods of non-biological synthesis lead to the formation of similar sets of aminoacids, in which there are many protein aminoacids. The analytical procedure developed recently makes it possible to detect a very large number of aminoacids present simultaneously in the mixtures synthesised.

The data quoted suggest that the problem of determining the principal pathways in the prebiological synthesis of aminoacids under laboratory conditions may be regarded as to a large extent solved. The possible discovery of new non-biological methods for their formation will confirm yet again the wide variety of natural pathways to the origin of life on Earth. The mechanism of the chemical conversion of simple starting materials into aminoacids, products with a highly developed polyfunctional structure, has many aspects, which are still unelucidated despite the large number of studies carried out. This applies particularly to the reactions occurring under the influence of ionising radiation, ultraviolet light, and heat, although in each case, including reactions under the influence of electric discharges, the excitation, activation, and ionisation processes have much in common, which is confirmed by the similarity of the products synthesised. In this connection, consistent efforts of investigators in the field of non-biological syntheses will probably be directed to a more systematic elucidation of the mechanisms of the formation of aminoacids.

It is interesting that all the protein and non-protein aminoacids discovered in the Murchison meteorite have been identified in a single experiment using electric discharges. There is a similarity not only between the qualitative but also the quantitative compositions of the products obtained in the laboratory experiment and discovered in the meteorite. One must emphasise yet again that the carbonaceous material in meteorites contains both aminoacids and their precursors—formaldehyde, hydrogen cyanide, and cyanoacetylene, i.e. compounds which are obtained in various non-biological syntheses. Together with the results of the analysis of lunar rocks, these data constitute evidence for universality of the prebiological pathways to the formation of aminoacids.

REFERENCES

1. A.I.Oparin, "Proiskhozhdenie Zhizni" (The Origin of Life), Izd."Moskovskii Rabochii", Moscow, 1924.
2. J.B.S.Haldane, Rationalist Annual, 148 (1928).
3. S.L.Miller, Science, 117, 528 (1953).
4. S.L.Miller, J.Amer.Chem.Soc., 77, 2351 (1955).
5. A.G.Pasynskii and T.E.Pavlovskaya, Uspekhi Khim., 33, 1198 (1964) [Russ.Chem.Rev., No.10 (1964)].
6. C.Ponnamperuma and N.W.Gabel, Symposium, "Vozniknovenie Organicheskogo Veshchestva v Solnechnoi Sisteme" (The Origin of Organic Matter in the Solar System) (Translated into Russian), Izd.Mir, Moscow, 1969, p.128.
7. R.H.Lemmon, Chem.Rev., 70, 95 (1970).
8. T.E.Pavlovskaya, Symposium, "Problemy Vozniknoveniya i Sushchnosti Zhizni" (Problems of the Origin and the Nature of Life), Izd.Nauka, Moscow, 1973, p.38.

9. A.A.Titaev, "Evolyutsiya, Organicheskikh Soedinenii na Zemle" (Evolution of Organic Compounds on Earth), Izd.Nauka, Moscow, 1974.
10. J.Oró, Space Life Sci., 3, 507 (1972).
11. V.G.Gorbatskii, "Kosmicheskie Vzryvy" (Cosmic Explosions), Izd.Nauka, Moscow, 1972.
12. W.I.Metz, Science, **182**, 466 (1973).
13. A.C.Cheung, D.M.Rank, C.H.Townes, D.D.Thornton, and W.S.Welch, Phys.Rev.Letters, 21, 1701 (1968).
14. A.C.Cheung, D.M.Rank, C.H.Townes, D.D.Thornton, and W.S.Welch, Nature, **221**, 626 (1969).
15. L.E.Snyder, D.Buhl, B.Zuckerman, and P.Palmer, Phys.Rev.Letters, 22, 626 (1969).
16. L.E.Snyder and D.Buhl, Astrophys.J., 163, L47 (1971).
17. B.E.Turner, Astrophys.J., 163, L35 (1971).
18. R.W.Wilson, K.B.Jefferts, and A.A.Penzias, Astrophys.J., 161, L43 (1970).
19. K.B.Jefferts, A.A.Penzias, and R.W.Wilson, Astrophys.J., 161, L87 (1970).
20. S.A.Ball, C.Z.Gottlieb, A.E.Lilley, and H.E.Radford, Astrophys.J., 162, L203 (1970).
21. B.Zuckermann, J.A.Ball, and C.Z.Gottlieb, Astrophys.J., 163, L41 (1971).
22. R.H.Rubin, G.W.Swenson, Jnr., R.C.Benson, H.L.Tigelaar, and W.H.Flygare, Astrophys.J., 169, L39 (1971).
23. P.M.Solomon, K.B.Jefferts, A.A.Penzias, and R.W.Wilson, Astrophys.J., 168, L107 (1971).
24. L.E.Snyder and D.Buhl, Bull.Amer.Astron.Soc., 3, 388 (1971).
25. E.Anders, R.Hayatsu, and M.Studier, Science, 182, 781 (1973).
26. D.Buhl and L.E.Snyder, Nature, **228**, 267 (1970).
27. S.K.Vsekhsvyatskii, "Priroda i Proiskhozhdenie Komet i Meteornogo Veshchestva" (The Nature and Origin of Comets and Meteoric Matter), Izd.Nauka, Moscow, 1968.
28. L.Biermann, Nature, 229, 156 (1971).
29. G.P.Vdovykin, Symposium, "Abiogenez i Nachal'nye Stadii Evolyutsii Zhizni" (Non-Biological Genesis and the Initial Stages in the Evolution of Life), Izd.Nauka, Moscow, 1968, p.23.
30. G.P.Vdovykin, "Uglerodistoe Veshchestvo Meteoritov" (The Carbonaceous Material in Meteorites), Izd.Nauka, Moscow, 1967.
31. E.Gelpi and J.Oró, Geochim.Cosmochim.Acta, 34, 981 (1970).
32. J.M.Hayes, Geochim.Cosmochim.Acta, 31, 1395 (1967).
33. J.Oró, S.Nakaparksin, H.Lichtenstein, and E.Gil-Av, Nature, **230**, 107 (1971).
34. S.W.Fox, K.Harada, and P.E.Hare, Proc.3d Lunar Sci.Conf., Geochim.Cosmochim.Acta, Suppl.3, 1972, p.2109.
35. P.E.Hare, in "Organic Geochemistry, Methods and Results" (Edited by G.Eglinton and M.T.I.Murphy), Springer-Verlag, New York, 1969, p.438.
36. K.A.Kvenvolden, Space Life Sci., 4, 60 (1973).
37. S.Nakaparksin, E.Gil-Av, and J.Oró, Analyt. Biochem., 33, 374 (1970).
38. J.L.Bada and R.A.Schroeder, Earth Planet Sci. Letters, 15, 1 (1972).
39. J.L.Bada, J.Amer.Chem.Soc., 95, 1371 (1972).
40. R.A.Schroeder and J.L.Bada, Science, **182**, 479 (1973).
41. F.B.Reed, J.Theor.Biol., 39, 683 (1973).
42. A.Meister, "Biochemistry of the Amino Acids", Vol.1, Acad.Press, New York, 1965, p.57.
43. M.G.Rutten, "The Origin of Life by Natural Causes" (Translated into Russian), Izd.Mir, Moscow, 1974, p.100.
44. K.Harada, P.E.Hare, C.R.Windsor, and S.W.Fox, Science, 173, 433 (1971).
45. H.Craig, Geochim.Cosmochim.Acta, 3, 53 (1953).
46. J.W.Shith and I.R.Kaplan, Science, 167, 1367 (1970).
47. K.Kvenvolden, J.Lawless, K.Pering, E.Peterson, J.Flores, C.Ponnamperuma, I.R.Kaplan, and C.Moore, Nature, 228, 923 (1970).
48. K.Kvenvolden, J.G.Lawless, and C.Ponnamperuma, Proc.Nat.Acad.Sci.U.S.A., 68, 486 (1971).
49. J.R.Cronin and C.B.Morre, Science, 172, 1327 (1971).
50. J.Oró, J.Gibert, H.Lichtenstein, S.Wikstrom, and D.A.Florey, Nature, 230, 105 (1971).
51. E.Gil-Av, R.Charles, and G.Fischer, J.Chromatog, 17, 408 (1965).
52. G.E.Pollock, V.I.Oyama, and R.D.Johnson, J. Gas.Chromatog., 3, 174 (1965).
53. K.Kvenvolden, E.Peterson, and G.E.Pollock, Adv.Org.Geochem., 387 (1971).
54. B.Halpern and J.W.Westley, Tetrahedron Letters, 21, 2286 (1966).
55. J.G.Lawless, K.A.Kvenvolden, E.Peterson, C.Ponnamperuma, and C.Moore, Science, 173, 626 (1971).
J.G.Lawless, C.E.Folcome, and K.A.Kvenvolden, Scientific American, 226, 38 (1972).
56. J.G.Lawless, K.A.Kvenvolden, E.Peterson, C.Ponnamperuma, and E.Jarosewich, Nature, 236, 66 (1972).
57. P.I.Abell, G.Eglington, S.R.Maxwell, C.T.Pillinger, and S.M.Hayes, Nature, 226, 251 (1970).
58. K.A.Kvenvolden, Space Life Sci., 3, 330 (1972).
59. S.Chang, K.A.Kvenvolden, S.Lawless, C.Ponnamperuma, and I.R.Kaplan, Science, 171, 474 (1971).
60. 4th Lunar Sci.Conf., in Science, 181, 615 (1973); 182, 659 (1973).
61. S.Chang and K.A.Kvenvolden, in "Exobiology" (Edited by C.Ponnamperuma), North-Holland Publ. Co., Amsterdam, 1972, p.400.
62. J.Oró, W.S.Updegrove, J.Gibert, J.McReynolds, E.Gil-Av, J.Ibanex, A.Zlatkis, D.A.Florey, R.L.Levy, and C.Wolf, Science, 167, 765 (1970).
63. C.W.Gehrke, R.W.Zumwalt, W.A.Aue, D.L.Stalling, A.Duffield, K.A.Kvenvolden, and C.Ponnamperuma, Proc.Apollo 11 Lunar Sci. Conf., Geochim.Cosmochim.Acta, Suppl.1, 2, 1845 (1970).
64. B.Nagy, C.M.Drew, P.B.Hamilton, V.E.Modzeleski, M.E.Murphy, W.M.Scott, H.C.Urey, and M.Young, Science, 167, 770 (1970).
65. P.E.Hare, K.Harada, and S.W.Fox, Proc.Apollo 11 Lunar Sci.Conf., Geochim.Cosmochim.Acta, Suppl.1, 2, 1799 (1970).
66. S.W.Fox, K.Harada, P.E.Hare, G.Hinsch, and G.Mueller, Science, 167, 767 (1970).
67. M.E.Murphy, V.E.Modzeleski, B.Nagy, W.M.Scott, M.Young, C.M.Drew, P.B.Hamilton,

and H.C.Urey, Proc.Apollo 11 Lunar Sci.Conf., Geochim.Cosmochim.Acta, Suppl.1, 2, 1879 (1970).
68. K.A.Kvenvolden, S.Chang, J.W.Smith, J.Flores, K.Pering, C.Saxinger, F.Woeller, K.Keil, I.Breger, and C.Ponnamperuma, Proc.Apollo 11 Lunar Sci.Conf., Geochim.Cosmochim.Acta, Suppl.1, 2, 1813 (1970).
69. K.A.Kvenvolden, in "Theory and Experiment in Exobiology" (Edited by A.W.Schartz), Wolters-Noordhoff Publ., Groningen, Netherlands, 1971, Vol.1, p.107.
70. P.I.Abell, C.H.Draffan, G.Eglinton, J.M.Hayes, J.R.Maxwell, and C.T.Pillinger, Proc.Apollo 11 Lunar Sci.Conf., Geochim.Cosmochim.Acta, Suppl.1, 2, 1757 (1970).
71. G.W.Gehrke, R.W.Zumwalt, D.L.Stalling, D.Roach, W.A.Aue, C.Ponnamperuma, and K.A.Kvenvolden, J.Chromatog., 59, 305 (1971).
72. A.A.Levinson (Editor), "Organic Geochemistry", Geochim.Cosmochim.Acta, Suppl.2, 2, 1841 (1970).
73. B.Nagy, J.E.Modzeleski, V.E.Modzelevski, M.A.Jabbar Mohammad, L.A.Nagy, W.M.Scott, C.M.Drew, J.E.Thomas, R.Ward, P.B.Hamilton, and H.C.Urey, Nature, **232**, 94 (1971).
74. S.F.Fox, K.Harada, and P.E.Hare, Space Life Sci., 3, 425 (1972).
75. S.W.Fox, K.Harada, and P.E.Hare, in "The Apollo 15 Lunar Samples" (Edited by J.W.Chamberlain and C.Watkins), Lunar Science Institute, Houston, 1972, p.299.
76. I.R.Kaplan and J.W.Smith, Science, 167, 541 (1970).
77. S.Epstein and H.P.Taylor, Science, 167, 533 (1970).
78. L.E.Snyder and D.Buhl, Sky Telesc., 40, 267 (1970); 345 (1970).
79. J.Oró, Nature, 190, 389 (1961).
80. H.R.Hulett, Science, 174, 1038 (1971).
81. S.W.Fox, K.Harada, G.Krampitz, and G.Mueller, Chem.Eng.News, 48, 80 (1970).
82. R.Woeller and C.Ponnamperuma, Icarus, 10, 386 (1969).
83. J.D.Bernal, "The Origin of Life on Earth" (Translated into Russian), Izd.Mir, Moscow, 1970.
84. A.P.Vinogradov, Sumposium, "Khimiya Zemnoi Kory" (The Chemistry of Earth's Core), Izd.Nauka, Moscow, 1964, Vol.2.
85. V.N.Florovskaya, Symposium, "Abiogenez i Nachal'nye Stadii Evolyutsii Zhizni" (Non-Biological Genesis and the Initial Stages in the Evolution of Life), Izd.Nauka, Moscow, 1968.
86. P.H.Abelson, Proc.Nat.Acad.Sci.U.S.A., 55, 1365 (1966).
87. V.A.Sokolov, "Geokhimiya Gazov Zemnoi Kory i Atmosfery" (The Geochemistry of the Gases in Earth's Core and Atmosphere), Izd.Nedra, Moscow, 1967.
88. D.Cruickshank, D.Morrison, and K.Lennon, Science, 182, 277 (1973).
89. L.M.Mukhin, Khimiya i Zhizn', 10 (1974).
90. G.Toupance, F.Raulin, and R.Buvet, in "Chemical Evolution and the Origin of Life" (Edited by R.Buvet and C.Ponnamperuma), North-Holland Publ.Co., Amsterdam, 1971, p.83.
91. S.L.Miller and H.C.Urey, Science, 130, 245 (1959).
92. S.L.Miller, Biochim.Biophys.Acta, 23, 480 (1957).
93. L.G.Sillén, Science, 156, 1189 (1967).
94. J.L.Bada and S.L.Miller, Science, 159, 423 (1968).
95. D.Ring, Y.Wolman, N.Friedmann, and S.L.Miller, Proc.Nat.Acad.Sci.U.S.A., 69, 765 (1972).
96. Y.Wolman, W.S.Haverland, and S.L.Miller, Proc.Nat.Acad.Sci.U.S.A., 69, 809 (1972).
97. R.Sanchez, J.Ferris, and L.Orgel, Science, 153, 72 (1966); 154, 784 (1966).
98. S.A.Miller, "Atsetilen, Ego Svoistva i Primenenie" (The Properties and Applications of Acetylene), Izd.Khimiya, Leningrad, 1969, Vol.1, p.359.
99. A.T.Soldatenkov, A.L.Lapidus, and N.S.Pechuro, Neftekhimiya, 7, 232 (1967).
100. E.A.Nevmerzhitskaya, A.N.Belyaeva, V.A.Poprotskaya, and N.A.Kudryavtseva, Khim.Prom., 41, 895 (1965).
101. N.Friedman and S.L.Miller, Science, 166, 766 (1969).
102. T.E.Pavlovskaya, A.G.Pasynskii, and A.I.Grebenikova, Dokl.Akad.Nauk SSSR, 135, 743 (1960).
103. M.A.Kolomiichenko, Ukrain.Biokhim.Zhur., 36, 216 (1964).
104. J.E.Van Trump and S.L.Miller, Science, 179, 859 (1972).
105. K.A.Grossenbacher and C.A.Knight, Symposium, "Proiskhozhdenie Prebiologicheskikh Sistem" (The Origin of Prebiological Systems) (Translated into Russian), Izd.Mir, Moscow, 1966, p.178.
106. P.H.Abelson, Ann.New York Acad.Sci., 69, 274 (1957).
107. T.E.Pavlovskaya and A.G.Pasynskii, Symposium, "Vozhniknovenie Zhizni na Zemle" (The Origin of Life on Earth), Izd.Akad.Nauk SSSR, Moscow, p.161.
108. C.Ponnamperuma, F.Woeller, J.Flores, M.Romier, and W.Allen, in "Chemical Reactions in Electric Discharges" (Edited by R.F.Gould), Adv.Chem.Ser., 80, 280 (1969).
109. C.Ponnamperuma and F.Woeller, Currents in Modern Biology, 1, 156 (1967).
110. M.S.Chadha, J.Lawless, J.Flores, and C.Ponnamperuma, in "Chemical Evolution and the Origin of Life" (Editors R.Buvet and C.Ponnamperuma), North-Holland Publ.Co., Amsterdam, 1971, p.143.
111. H.Noda and C.Ponnamperuma, in "Chemical Evolution and the Origin of Life" (Editors R.Buvet and C.Ponnamperuma), North-Holland Publ.Co. Amsterdam, 1971, p.236.
112. C.N.Matthews and R.E.Moser, Proc.Nat.Acad.Sci.U.S.A., 56, 1087 (1966).
113. R.E.Moser, A.R.Claggett, and C.N.Matthews, Tetrahedron Letters, 13, 1599 (1968).
114. F.Balestic, J.Chim.Phys.et Phys.-chim.Biol., 70, 169 (1973).
115. R.A.Bernheim, R.J.Kempf, P.W.Hunter, and P.S.Skell, J.Chem.Phys., 41, 1156 (1964).
116. R.G.Freeman, Canad.J.Chem., 44, 245 (1966).
117. W.Groth and H.V.Weyssenhoff, Ann.Phys., 7, 69 (1959).
118. A.N.Terenin, Symposium, "Vozniknovenie Zhizni na Zemle" (The Origin of Life on Earth), Izd.Akad.Nauk SSSR, Moscow, 1959, p.144.
119. N.Ya.Dodonova, A.I.Sidorova, and A.N.Terenin, Vesnik Leningrad.Univ., 14, 33 (1959).
120. C.Sagan, Symposium, "Proiskhozhdenie Prebiologicheskikh Sistem" (The Origin of Prebiological Systems) (Translated into Russian), Izd.Mir, Moscow, 1966, p.111.

121. T.E. Pavlovskaya and A.G. Pasynskii, Symposium, "Problemy Evolyutsionnoi i Tekhnicheskoi Biokhimii" (Problems of Evolutionary and Technical Biochemistry), Izd. Nauka, Moscow, 1964, p. 70.
122. T.E. Pavlovskaya, A.G. Pasynskii, V.S. Sidorov, and A.I. Labyzhenskii, Symposium, "Abiogenez i Nachal'nye Stadii Evolyutsii Zhizni" (Non-Biological Genesis and the Initial Stages in the Evolution of Life), Izd. Nauka, Moscow, 1968, p. 41.
123. R.A. Niskanen, T.E. Pavlovskaya, T.A. Telegina, V.S. Sidorov, and V.A. Sharpatyi, Izv. Akad. Nauk SSSR, Ser. Biol., 238 (1971).
124. A. Hellmer, J. Masanet, and C. Vermeil, J. Chem. Phys., 55, 1022 (1971).
125. J. Masanet and C. Vermeil, J. Chim. Phys., 66, 1249 (1969).
126. V.S. Sidorov, Dokl. Akad. Nauk SSSR, 164, 692 (1965).
127. M.A. Khenokh and N.P. Bogdanova, Dokl. Akad. Nauk SSSR, 182, 715 (1968).
128. E.M. Lapinskaya and M.A. Khenokh, Zhur. Evol. Biokhim. Fiziol., 7, 14 (1971).
129. E.M. Lapinskaya, M.A. Khenokh, and A.M. Skupskaya, Dokl. Akad. Nauk SSSR, 191, 1179 (1970).
130. K. Harada and S. Fox, Nature, 201, 335 (1964).
131. M. Taube, St. Z. Zdrojewski, K. Samochocka, and K. Jerierska, Angew. Chem., 79, 239 (1967).
132. J. Oró, Nature, 197, 862 (1963).
133. J. Oró, Symposium, "Proiskhozhdenie Prebiologicheskikh Sistem" (The Origin of Prebiological Systems) (Translated into Russian), Izd. Mir, Moscow, 1966, p. 144.
134. J.G. Lawless and C.D. Boynton, Nature, 243, 405 (1973).
135. V.N. Florovskaya, Symposium, "Problemy Vozniknoveniya i Sushchnosti Zhizni" (Problems of the Origin and the Nature of Life), Izd. Nauka, Moscow, 1973, p. 23.
136. S.W. Fox, Ann. New York Acad. Sci., 194, 71 (1972).
137. M.H. Studier, R. Hayatsu, and E. Anders, Geochim. Cosmochim. Acta, 32, 151 (1968).
138. R. Hayatsu, M.H. Studier, and E. Anders, Geochim. Cosmochim. Acta, 35, 939 (1971).
139. D. Yoshino, R. Hayatsu, and E. Anders, Geochim. Cosmochim. Acta, 35, 927 (1971).
140. S.W. Fox and C.R. Windsor, Science, 170, 984 (1970).
141. S.W. Fox and C.R. Windsor, Science, 174, 1040 (1971).
142. Y. Wolman, S.L. Miller, J. Ibanez, and J. Oró, Science, 174, 1039 (1971).
143. A. Butlerow, Annalen, 115, 322 (1860).
144. J. Oró, in "Current Aspects of Exobiology" (Edited by G. Mamikunian and M.H. Briggs), Pergamon Press, London, 1965, p. 13.
145. R.E. Moser and C.N. Matthews, Experientia, 24, 658 (1968).
146. A.S.U. Choughuley, A.S. Subbaraman, and Z.A. Kazi, Indian J. Biochem. Biophys., 9, 144 (1972).
147. F. Friedmann, W.J. Haverland, and S.L. Miller, in "Chemical Evolution and the Origin of Life" (Edited by R. Buvet and C. Ponnamperuma), North-Holland Publ. Co., Amsterdam, 1971, p. 123.
148. A.S. Subbaraman, Z.A. Kazi, and A.S.U. Choughuley, Indian J. Biochem. Biophys., 9, 268 (1972).
149. C. Palm and M. Calvin, J. Amer. Chem. Soc., 84, 2115 (1962).
150. A. Choughuley and R. Lemmon, Nature, 210, 628 (1966).
151. K. Dose and B. Rajewsky, Biochim. Biophys. Acta, 25, 225 (1957).
152. K. Dose and S. Risi, Z. Naturforsch., 23b, 581 (1968).
153. I.E. El'piner, Symposium, "Abiogenez i Nachal'nye Stadii Evolyutsii Zhizni" (Non-Biological Genesis and the Initial Stages in the Evolution of Life), Izd. Nauka, Moscow, 1968, p. 49.
154. A. Bar-Nun, N. Bar-Nun, S.H. Bauer, and C. Sagan, Science, 168, 470 (1970).
155. A. Bar-Nun, N. Bar-Nun, S.H. Bauer, and C. Sagan, Science, 170, 1001 (1970).
156. A. Bar-Nun, S.H. Bauer, and C. Sagan, US P. 3652434; Chem. Abs., 77, 20019 (1972).

Department of Organic Chemistry,
University of Friendship among
Nations