Research on Cosmic Matter on the Earth and in Space;
Research on the Biological and Geochemical Specifics of the Early Earth

<u>Contents</u>

Introduction

Astrobiology is a rapidly developing science which studies life in the broadest sense, that is, as a universal space phenomenon: its origin, evolution, and presence in the Universe. Astrobiologists strive for a fuller understanding of terrestrial life to optimize the search for life on other planets. It is necessary to come closer to answering the following fundamental questions: Where and under what conditions could the first organisms originate? What were the conditions of their existence? Are there any other habitable space bodies in the Solar System? Astrobiology also studies the processes from astrocatalysis — the formation of the first organic compounds in space — to the formation of cells and, further, the first organisms.

The present Project pertains to astrobiology. In recent years, astrobiological research has gained special relevance as there has been increasing evidence of the presence of life in the Universe. New limits have been found of the existence of living organisms (extremophiles) on Earth; fossilized microorganisms have been found in meteorites; organic molecules have been known to be highly incident in space.

In the fields presented in the Project, important astrobiological research is performed, which has already yielded significant results. The theme is conducted by the Astrobiology Sector of the Laboratory of Radiation Biology (JINR) with the participation of JINR's other subdivisions and collaborating scientific institutions. A number of studies are done jointly; some of them are performed at collaborators' facilities.

Project validation

It is known that different organic compounds are present in space, including complex ones, which might have been progenitors of the currently known form of life. They are relatively stable in the interstellar medium, but during the formation of planets from gas-dust disks, they can undergo different chemical transformations. Such molecules can become part of meteorites and comet nuclei and be transferred by them to forming and already formed planets. This all, along with the discovery of Earth-like planets and fossilized microorganisms in meteorites, suggests that life must be present in the Universe.

Radiobiological research requires biological, astrophysical, physical, chemical, and paleontological techniques. A huge amount of cosmic (meteorite) matter is continuously deposited on Earth, which is one of the significant stimuli for the development of astrobiology. The discovery of fossilized microorganisms (microfossils) in meteorites made it necessary to reconsider the concept of panspermia.

The idea that microorganisms were brought on Earth from outside has always been limited by the problem of their survival and transportation in space. From this point of view, one of the main fields of research is studying prolonged anabiosis of microorganisms in Antarctic ice and in permafrost. It has been established that life has an unbelievable ability to adapt to the most diverse, including extreme, conditions. This prompts a new approach to studying the possibilities of life on Solar system planets, their moons, asteroids, and comets, as well as in the interstellar and interplanetary medium. Of great importance is the discovery of microfossils and life molecules in meteorites.

To continue astrobiology development in Russia, a new research theme was started at JINR in 2013 with the support of the Scientific Council on Astrobiology at the Presidium of the Russian Academy of Sciences: *"Biogeochemical Research on Cosmic Matter on the Earth and in Space; Research on the Biological and Geochemical Specifics of the Early Earth"*

The Astrobiology Sector of the Laboratory of Radiation Biology, JINR, conducts research in the following fields:

- studying microfossils and organic compounds in meteorites and ancient terrestrial rocks; studying cryosphere as a model of possible ecosystems on Mars and glacial moons of planets;
- studying life in extremely hot and cold conditions;
- research on the synthesis of complex prebiotic compounds from formamide under exposure to radiation in the presence of meteorites and terrestrial rocks as catalysts;
- biogeochemical studies of cosmic dust;
- studying cosmic matter with nuclear physics methods;
- research on the possible transfer of life between bodies of the Solar System and beyond;
- early Earth studies: paleontological, paleobiological, geological, and other aspects; possible models of the origin of life on Earth; formation of the RNA world;
- studying organic compounds in, and physical and chemical parameters of, hydrothermal systems, Earth's subterranean biosphere, and cosmic matter in the context of the origination of the primary forms of life on the early Earth and other planets.

Among these fields of research, the main ones are the following:

- studying microfossils and organic compounds in meteorites and ancient terrestrial rocks;
- research on the synthesis of complex prebiotic compounds from formamide under exposure to radiation with meteorites involved as catalysts;
- biogeochemical studies of cosmic dust; cosmic matter research with nuclear physics methods.

As part of this research, a number of specific activities will be performed, including —

- studies of the possible sources, ways, and conditions of the formation of the first prebiotic compounds;
- a search for traces of life in meteorites and other astromaterials;
- studies of variations in the elemental and mineral composition of meteorites;
- studies of extremophile organisms;
- interpretation of cosmic dust research results;
- micropaleontological studies of terrestrial rocks due to Earth being the most studied object of the Solar System.

For the solution of the stated problems, gas chromatography and mass spectrometry (GC/MS), electron microscopy, energy dispersive X-ray spectrometry, and other techniques will be used.

1. *Studies of microfossils and organic compounds in meteorites and ancient terrestrial rocks*

Microfossils are petrified microorganisms and products of their vital activity. They are important evidence of life occurrence in the Universe. Microfossils are present practically in all sedimentary and volcanogenic sedimentary rocks of the Earth's crust beginning with 3.9 billion years ago. Based on the experience acquired in bacterial paleontology, microfossils were confidently isolated from carbonaceous chondrite meteorites, some of which can be older than the Earth. This can point to the fact that life in the Solar System emerged outside of the Earth and was probably brought to the Earth from space. Studying microfossils and organic compounds in meteorites and ancient terrestrial rocks will allow obtaining data on the forms of ancient terrestrial and extraterrestrial life and clearing up the problem of the origin of life.

The elemental and mineral composition of meteorites and terrestrial rocks is going to be studied with energy dispersive X-ray microanalysis. Knowing meteorites' composition will allow making conclusions on their origin and conditions on their parent body.

Meteorite research requires differentiation between the ancient microfossils that are native to the meteorite and the terrestrial contaminants and abiogenic structures. As it is a matter of pseudomorphoses, whose chemical composition does not differ from that of the meteorite, in the first case contamination is detected with a microanalyzer. In the latter, the biogenic structures, as a rule, are strongly different morphologically from the abiogenic ones.

Micropaleontological studies of the most ancient terrestrial rocks will broaden our knowledge of early Earth's conditions and the history of the development of life on it.

Extremophile research will help determining the limits of living species existence. At the Astrobiology Sector, it is planned to conduct SEM studies of such organisms' morphology.

With a Tescan Vega 3 scanning electron microscope, more than 20 meteorite and terrestrial rock samples have been studied at the Astrobiology Sector. Several hundred images of fossil microorganisms have been obtained and analyzed.

Research has been continued on the most ancient weathering rinds and Archean and early Proterozoic ferruginous quartzites of Karelia, Kola Peninsula, and Kursk Magnetic Anomaly; new data have been obtained on the biogenic origin of minerals; the role of organisms in the concentration of minerals on Earth has been evaluated; issues have been considered of the microorganism colonization of lava flows and land.

As part of collaboration with Borisyak Paleontological Institute RAS, its Senior Scientist M.M. Astafieva *et al.* have conducted a series of bacterial paleontology studies.

2. *Research on the synthesis of complex prebiotic compounds from formamide under exposure to radiation with meteorites involved as catalysts*

As is known, meteorites have inside a significant amount of organic substances, many of which are necessary for the origination of life. It is assumed that they were synthesized during the gas phase and then were integrated into minerals. Studying the synthesis of these prebiotic compounds makes it possible to approach the answer to the question, "How could so complex structures develop on meteorites?" Once on Earth, these compounds might have originated life on Earth. The transition "from the inanimate to live" is still unclear, but the early stages of this process can be reproduced experimentally.

In particular, formamide (FA) ($HCONH_2$) — one of the simplest chemical compounds which is common both in the interstellar and interplanetary media — might have been such "initial material". The research performed at the Astrobiology Sector in cooperation with scientists of the University of Tuscia (Viterbo, Italy) has shown that more complex organic molecules can form from FA, including amino acids, carboxylic acids, sugars, nucleic bases, and even nucleosides. This diverse synthesis takes place when a mixture of FA and meteorite matter is exposed to ionizing radiation. After irradiation, a GC/MS method was used to identify the organic compounds in a complex mixture. Studying the action of different radiation types on FA mixed with meteorite matter can thus allow solving the fundamental problem of the formation of prebiotic compounds, which in turn underlie the formation of the first living systems. It is a pioneering research as modern studies of organic compound synthesis from FA mainly involve the temperature factor or UV radiation, which limits the research results to the synthesis of simpler compounds than have been obtained at the Astrobiology Sector.

3. *Biogeochemical studies of cosmic dust*

Cosmic dust (CD) research allows obtaining data on the regularities of the time distribution of the cosmic dust falling on the Earth surface, which is important for the reconstruction of the Earth's geological history and paleoclimate evaluation. Research on the CD structure, chemical and isotope composition, and biological properties helps solving fundamentals problems like the nature of interplanetary matter and its role in the origin of life. Therefore, of special interest is the detection of organic compounds in CD. Studying the physical and chemical properties of CD particles and comparing them with those of asteroids and comet nuclei determined by distance methods allows obtaining valuable information on the origin and evolution of not only these cosmic bodies but the Solar System as a whole.

CD forms mainly in the course of periodic comet disruption and asteroid fragmentation. The interplanetary medium also includes interstellar dust particles. Probably, they get into the Solar System due to accretion when interstellar dust passes through interstellar gas- dust clouds. Light scattering by interplanetary dust particles is accompanied by optical phenomena, such as zodiacal light, the Fraunhofer component of the solar corona, the zodiacal band, and counterglow.

Of special interest is the CD that falls on the Earth's surface. It is found in deep marine and ocean sediments, the ice and snow cover of the Arctic and Antarctic, mountain snow cover, rock strata, and other natural terrains. Cosmic dust is an important source of matter and energy that continuously come to Earth from space, actively influencing geochemical and geophysical processes and affecting biological objects, including the humans.

CD studies are conducted according to the CD Research Program of the Scientific Council on Astrobiology of the RAS Presidium in cooperation with a number of scientific institutions.

Within the framework of the Project, particles' morphology, size, and elemental, isotope, and mineralogical composition were determined. Special consideration was given to studying organic compounds. The most important task was to isolate the cosmogeneous component of the collected samples.

During the reporting period, the Astrobiology Sector worked toward the establishment of the center of the collection, storage, and distribution of samples that are valuable for astrobiological research: meteorites and CD; soil, ice, and snow with cosmic dust traces; etc. Shelves, sterile and unsterile containers, etc. are available in proper amounts. To systemize information on the samples delivered to the center and to monitor their storage, a MySQL web-oriented database was developed. The sector is ready to accept samples and store them under specified external conditions for further research: a cooling chamber and a freezing chamber with a volume of more than 200 L are available.

The Program includes the following fields of research:

- CD collection in different natural terrains (Arctic and Antarctic snow and ice, high mountain snow and ice, peat moss, rock strata, bottom sediments, the upper atmosphere, near-Earth space, and interplanetary space;
- Isolation (enrichment) of the space component of the collected dust samples;
- Comprehensive analysis of the space component of dust, including —
    - studying the mineralogical, chemical, and elemental composition of CD;
    - determination of the isotope composition of CD reference elements;

- search for biomarkers, including blocks and, probably, whole molecules of hereditary information of the nucleic acid type, as well as living microorganisms in CD;
- estimation of the total amount of CD falling on the Earth surface;
- evaluation of the CD spatial distribution over the Earth surface and its temporal variations; studying CD composition variations in the Earth's geological history;
- comparative analysis of fossil and "modern" CD using interplanetary dust collected by spacecraft as reference samples (as they are not contaminated with terrestrial dust);
- research on CD influence on the Earth's paleoclimate;
- research on CD influence on the biological objects, including microflora (soil fertility).

The most important task is the isolation of the cosmogeneous component from the collected samples. In this connection, it is planned to establish at the Astrobiology Sector of the LRB (JINR) a *single center* of the collection, storage, distribution, and studies of CD samples (including nuclear physics methods); and preparation of CD samples for different types of analysis. A special task will be to create and support a CD *data bank* for information collection, storage, and dissemination. It will be necessary to provide sample storage at negative temperatures and sample preparation under clean room conditions.

The specific activities within the framework of the proposed Project in its part "Biogeochemical studies of cosmic dust" will include –

1) CD dust collection in the ice and snow cover of the Central East Antarctic;
2) ice and snow processing and melting under clean room conditions;
3) CD microparticle concentration under clean room conditions;
4) evaluation of the CD microparticle concentration and distribution by size under clean room conditions (with a Beckman Coulter particle counter);
5) preparation of CD microparticle samples under clean room conditions for different types of analysis at the level of separate particles (morphology; elemental and mineralogical composition; possibly, the isotope composition of a number of elements; in future, organic component research) using mainly electron microscopes and collaborators' probe attachments;
6) aerogel design and production; placing an aerogel-containing CD particle catcher at the Photon-M spacecraft.

4. *Cosmic matter research with nuclear physics methods*

Opening this topic at JINR allowed using nuclear physics methods for cosmic matter research. These methods include —

- determination of the elemental composition of cosmic dust (CD) and other materials of extraterrestrial origin using multi-element neutron activation analysis (NAA) at the IBR-2 reactor;
- identification of heavy isotopes with the IREN neutron spectrograph;
- determination of sample structure by X-ray and neutron tomography methods.

At the NAA Sector of the Laboratory of Neutron Physics, JINR, experience in studying microparticles of industrial origin using peat moss has been acquired during many years. The special feature of this moss, which grows over large areas of Eurasia, is that it receives nutrition only from the atmosphere. Therefore, the microparticles found in it are of atmospheric origin. For more than 15 years, the NAA Sector has been participating in the international program "Heavy Metal Atmospheric Deposition in Europe – Estimations Based on Moss Analysis" and submitting to the European Atlas of Heavy Metals in Atmospheric Precipitation, which is issued every five years by the United Nations Economic Commission for Europe, results of the analysis of moss samples collected in Central Russia, Urals, and a number of countries, including Albania, Bulgaria, Croatia, Macedonia, Poland, Romania, Serbia, Slovakia, and more.

Peat moss can also be used as a CD accumulator. Unlike the Ecology Program requirement that samples be collected near industrial centers, samples for CD research must be collected far from them. The sample collection methodology, which allows obtaining the time section, was developed by Siberian scientists and was efficiently used by them, in particular, for studying the Tunguska phenomenon. It can also be used by the Ecology Program collaboration in CD research.

The NAA Sector also studied the magnetic fraction of CD samples from the Ak-Tru glacier region in the Altai mountains. NAA, along with other methods, is now used for studying Antarctic and fossil dust samples.

As regards the cosmogeneous component, its important indicator is *iridium content*. For its registration and for detecting other heavy isotopes, the IREN pulsed neutron source at the Laboratory of Neutron Physics, JINR, can be used. Research will be based on neutron resonance capture analysis (NRCA). Its application is limited to the detection of light elements ($Z \leq 14$) but is more efficient for elements with $Z \geq 28$. NRCA advantages also include its non-destructiveness; the possibility of studying relatively large samples of any shape; the absence of residual induced radioactivity; and sensitivity to the isotope composition of the sample. The latter can be promising for identifying the cosmogeneous component of CD-containing samples and for studying other samples of extraterrestrial origin.

Within this field of research, the following specific activities are performed:

1. CD-containing sample collection in Western Siberia, in the Altai Mountains, and in bottom sediments of the Atlantic Ocean.
2. Multi-element NAA of Siberian turf columns and magnetic particles from the Ak-Tru glacier (Kosh-Agachsky District, the North Chuisk Range in the southeast of the Altai Republic) at the IBR-2 reactor and at the Analytical Center of the RAS Geological Institute.
3. CD particle visualization with a scanning electron microscope and X-ray energy dispersion particle analysis (EDAX).
4. NAA and radiometry of bottom sediments at the Laboratory of Neutron Physics and Bucharest University, Romania.
5. Isotope analysis of samples from the Ak-Tru glacier at the IREN facility.
6. Determination of the structure specifics of CD particles with methods used in condensed matter analysis.

Results obtained in 2016–2019

1. Studies of microfossils and organic compounds in meteorites and ancient terrestrial rocks

With a Tescan Vega 3 scanning electron microscope, more than 20 samples of meteorites (first of all, the Orgueil and Murchison carbonaceous chondrites) and terrestrial rocks have been studied at the LRB Astrobiology Sector. Several hundred images of fossil microorganisms have been obtained and analyzed (Fig. 1), including cyanobacteria, actinomycetes, prasinophytes, testate amoebae, alveolates, etc. Some of the results of these studies were reported to the working meeting "Modern Problems of Space Radiobiology and Astrobiology" (17–19 October 2018, Dubna) by R. Hoover [1].. For the first time, pennate diatoms have been found in the Orgueil meteorite [2]. A micropaleontological research on early Precambrian rocks has been performed at Borisyak Paleontological Institute RAS. All bacterial paleontology studies have been done using a CamScan-4 scanning electron microscope (SEM) with a Link-860 microanalyzer, Zeiss EVO 50 SEM with an INCA Oxford 350 X-ray microanalyzer, and a Tescan Vega 2 ZMU SEM with an INCA Energy 450 system for energy dispersive X-ray

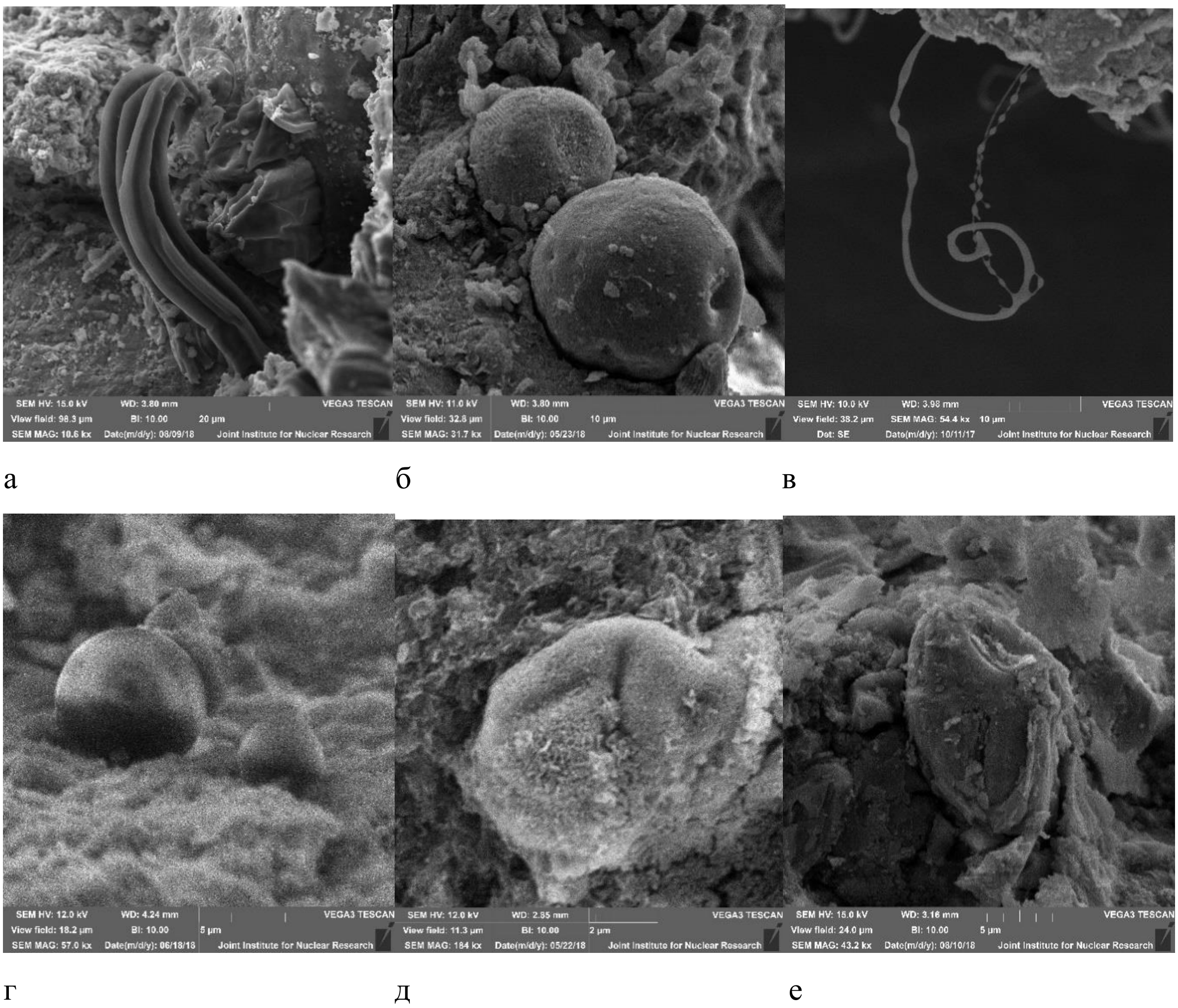

Fig. 1. Microfossils from the Orgueil *(a–e)* and Murchison *(f)* meteorites: a cyanobacterial filament *(a);* prasinophyte cells (pores are seen) *(b);* actinomycete filaments (*c);* testate amoebas *(d);* a pollen-like form *(e);* an alveolate *(f).*

microanalysis. Only fresh cleavages of rocks (ancient and modern) were used — sometimes, slightly etched by acids. It should be noted that the research deals with pseudomorphoses, not with fossilized microorganisms.

Research has been continued on the most ancient weathering rinds (Fig. 3) and Archean and early Proterozoic ferruginous quartzites of Karelia, Kola Peninsula, and Kursk Magnetic Anomaly [3,4,5,6]; new data have been obtained on the biogenic origin of minerals; the role of life in the concentration of minerals on Earth has been evaluated; issues have been considered of the microorganism colonization of lava flows [7] and land [8,9].

In the collective monograph Life and the Universe, M.M. Astafieva has presented results of a micropaleontological study of low Proterozoic pillow lavas of Karelia and South Africa, where various pseudomorphoses of biogenic objects have been found. It has been concluded that

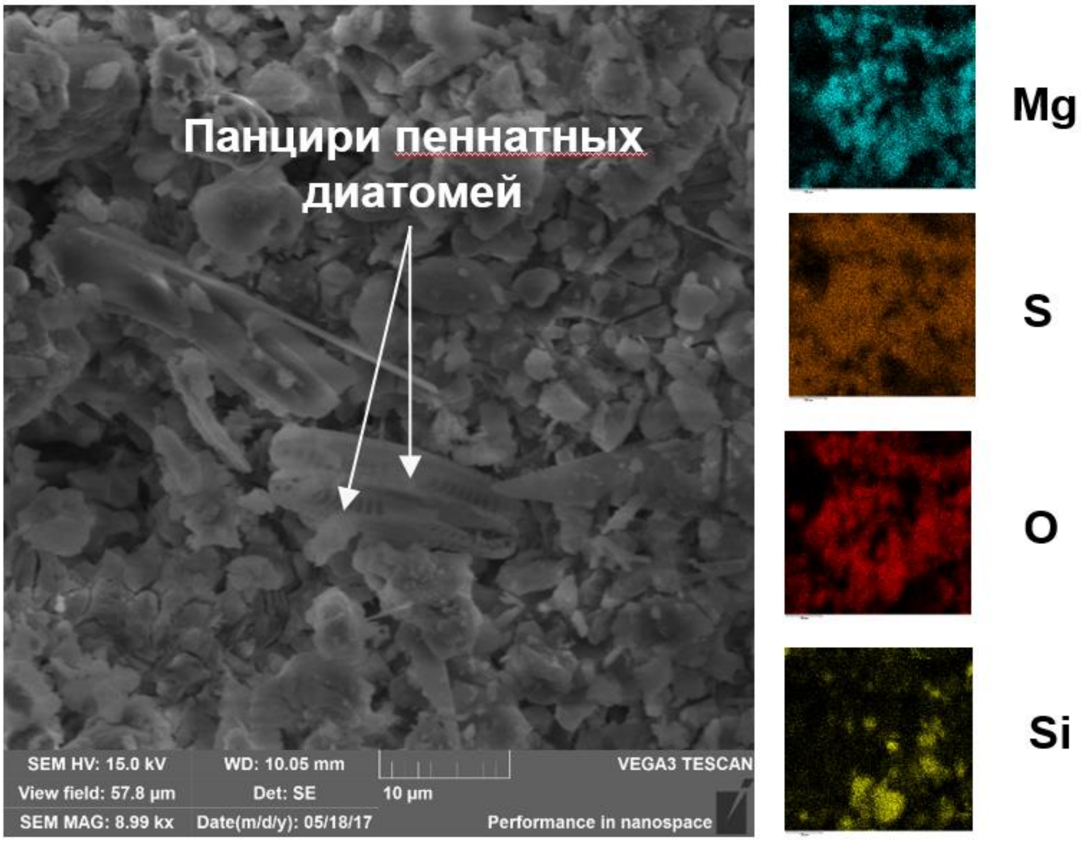

Fig. 2. Pennate diatoms in the Orgueil meteorite and energy dispersive spectrometry maps of the elemental distribution. The arrows point to pennate diatom shells.

the microorganism colonization of Earth could have started after Earth's crust had cooled down to 113ºC (other data indicate 120–130ºC); colonization processed along fractures and surfaces; and water provided protection from hard UV radiation.

In early Proterozoic ferruginous quartzites of the Kursk Magnetic Anomaly (the Lebedinsky mine; limonite-martite ores and striated ferruginous quartzites of the Korobkovsky ore deposit), fossilized cyanobacteria have been found, represented by trichomes merged into a single cover [3]. The minerals are deposited in situ. Morphologically, they are close to the modern representatives of the genus Microcoleus.

In striated ferruginous quartzites aged 2.7—2.8 billion years (the Archean Eon) from deposits in Karelia and the Kola Peninsula, microfossils of an apparently bacterial origin were found [6]. On the basis of an evaluation of organic carbon content and balance calculations, it has been established that the formation of the studied Archean ferruginous quartzites took place in a medium enriched with organic matter. A comparative analysis of the morphology of modern and Neoarchean microorganisms suggests a bacterial origin of some amount of magnetite in the studied quartzites.

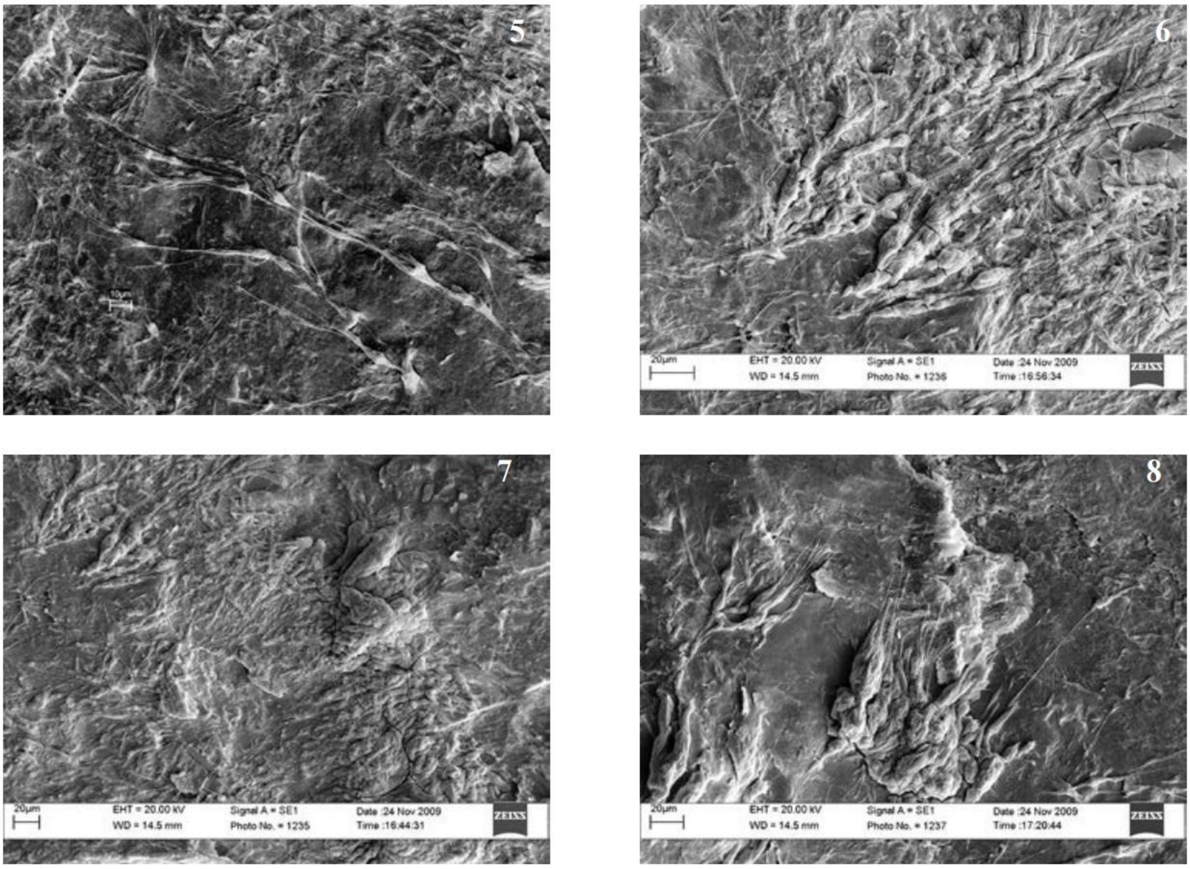

Fig. 3. Highly organized fossilized alga-like *Gazavarzinia antiqua* (Rozanov, Astafieva, 2013) forms (Imandra — Varzuga, PR_1, 2.45 billion years). (5–7) Intricately ramified main stems (about 10 μm in diameter) and ramified lateral branches (about 5 μm in diameter) are seen. (8) Flat round-oval bases, or patches (over 50 μm in size), by which algae attached to the substrate.

The results of microfossil research indicate that the biogenic factor played an important role in the formation of sedimentary early Proterozoic ferruginous quartzites of the Kursk Magnetic Anomaly. It was confirmed by finding cyanobacteria and abundant glycocalyx in fossil samples. It follows from here that sedimentary ferruginous quartzites were being deposited in the photic zone conditions — that is, in shallow water — and O_2 content in the atmosphere was quite high.

In early Precambrian Keiv proto-schists (the Kola Peninsula), nanobacteria deposited *in situ* were found. It is suggested that the presence of nanobacteria points to the involvement of the biological factor in the formation of host rocks; also, the presence of biofilms and nanobacteria suggests that the conditions of the external medium were unfavorable for bacterial life.

As part of the cooperation with Borisyak Paleontological Institute RAS, its Senior Scientist M.M. Astafieva *et al.* have conducted a series of bacterial paleontology studies of Precambrian rocks [10,11,12]. In particular —

- in early Precambrian Keiv paraschists (the Kola Peninsula), *in situ* buried nanobacteria have been discovered. It is suggested that the presence of nanobacteria indicates the biological factor's participation in the formation of enclosing strata;
- Volcanogenic and volcanogenic sedimentary rocks (early Proterozoic pillow lavas of Karelia and South Africa) were studied and found to contain different fossilized bacteria and, possibly, even eukaryotes. It was shown that at that early time the conditions for the development of life and colonization of cooling lava flows and volcanogenic rocks were favorable;

The current knowledge of the Archean microorganisms was assessed.

Acad. A.Yu. Rozanov [13] performed an analysis of the past two decades of astrobiological research. On the basis of this study —

- it was suggested that remains of eukaryotic algae are present in the Low Archean rocks of the Isua formation;
- the oxygen-free character of the Archean and early Proterozoic atmosphere was called into doubt;
- it was concluded that water did not appear on Earth in significant amounts earlier than 4 billion years ago;
- the time of the probable emergence of the RNA world was extended to 7 billion years ago.

Based on the example of archaeocyathan evolution (A.Yu. Rozanov, 2018), the importance has been shown of the ideas on evolution proposed by N.I. Vavilov, L.S. Berg, D.N. Sobolev, etc; and the creative role of natural selection has been questioned.

2. *Research on the synthesis of complex prebiotic compounds from formamide under exposure to radiation with meteorites involved as catalysts*

In 2016, research was continued on the synthesis of prebiotic compounds from formamide with meteorites as catalysts under exposure to radiation. Materials were published on irradiation with boron ions [14]. A repeat 170 MeV proton irradiation of mixtures of formamide and different meteorite samples was performed. Another type of sample analysis was performed: Raman spectroscopy. 18 samples of meteorite matter and terrestrial minerals were used in the experiment (the meteorites: Campo del Sielo, Canyon Diablo, Sikhote-Alin, Seymchan, NWA4482, NWA2828, Gold Basin, Dhofar959, NWA1465, NWA5357, Al Haggounia, and Chelyabinsk; the minerals: covellite CuS, chalcopyrite $CuFeS_2$, montmorillonite KSF, and Alpillared montmorrilonite KP-30) in a mixture with formamide. This research was done in collaboration with the Biophotonics Laboratory of the Institute of Electronics, the Bulgarian Academy of Sciences. The study was based on using a state-of-the-art inVia Qontor Raman microscope (the Renishaw company) at the Faculty of Nano- and Biomedical Technologies, Saratov Chernyshevsky State University, with which the LRB's Bulgarian colleagues are cooperating. The acquired spectra are being analyzed. Preliminary results indicate that nucleic bases and nucleosides were present the reaction mixtures (Table 1).

Table 1. Raman spectroscopy results of the irradiation of a formamide — meteorite/mineral matter mixture: a list of the identified nucleic bases and nucleosides.

Uracil	Cytosin	Hypoxanthine	Adenine	Guanine
4,6-DHP	Mannose	2,6-Diaminopurine	Orotic acid	Isocytosine
Thymine	Yhymidine	2`-Deoxyribose	Ribose	Adenosine
Glucose	Galactose	3(OH)pyridine	Uridine	Cytidine

Experiments were conducted in 2016 on the synthesis of DNA and RNA component nucleosides by irradiating a nucleic base — sugar mixture with a 170 MeV proton beam. As sugars, ribose and 2-deoxyribose were used. A nucleoside — phosphate group mixture was exposed to the same radiation in search of a possible synthesis of nucleotides that are DNA and RNA building blocks. The results were analyzed in Viterbo, Italy. Based on the preliminary results, it can be confidently said that irradiation of an adenine — deoxyribose mixture (Fig. 4) yielded, besides other molecules, deoxyadenosine and polyribosylated adenosine (Fig. 5). Formation of nucleosides under abiotic conditions is the main obstacle to research on the origin of life. In 2017, experiments were conducted on the synthesis of RNA and DNA component nucleosides in a formamide (FA) — meteorite matter system exposed to ionizing radiation (accelerated protons). Matter of chondrite meteorite NWA 1465 was used as a synthesis catalyst. The pathway was determined of the general reaction leading to the synthesis of ribo- and 2'-deoxyribonucleasides from sugars and purine nucleotides under exposure to 170 MeV protons in the presence of NWA 1465 matter — these factors simulate the supposed conditions in space or on early Earth. The reaction requires neither pre-activated precursor molecules nor any intermediate stages. The synthesis is based on a certain radical mechanism and is characterized by stereoselectivity, regioselectivity, and (poly)glycolysis. The yield of the reaction products is much higher in the presence of formamide and meteorite matter than in the control (Table 2). The results were published in *Scientific Reports,* a Nature Research journal [15].

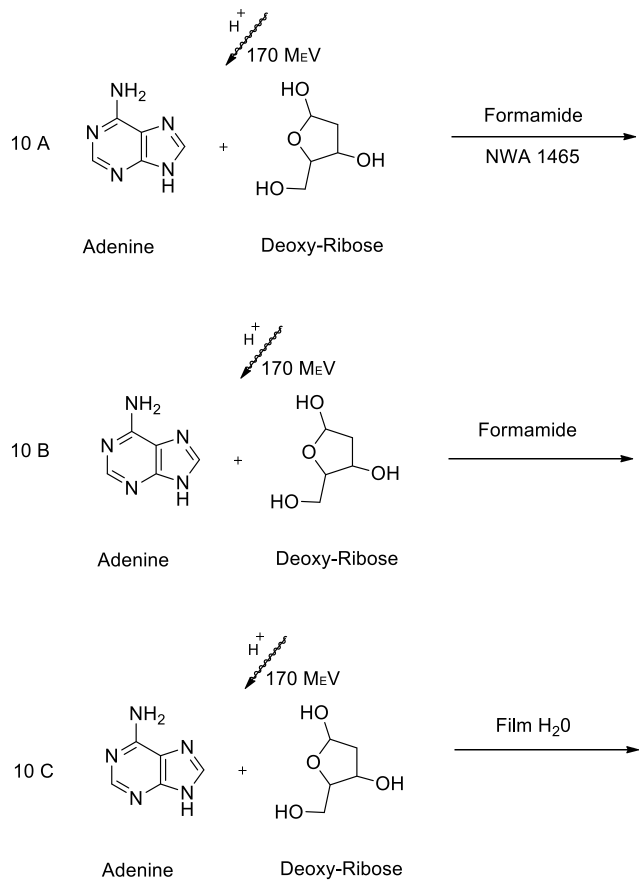

Fig. 4. A scheme of adenine — deoxyribose mixture irradiation.

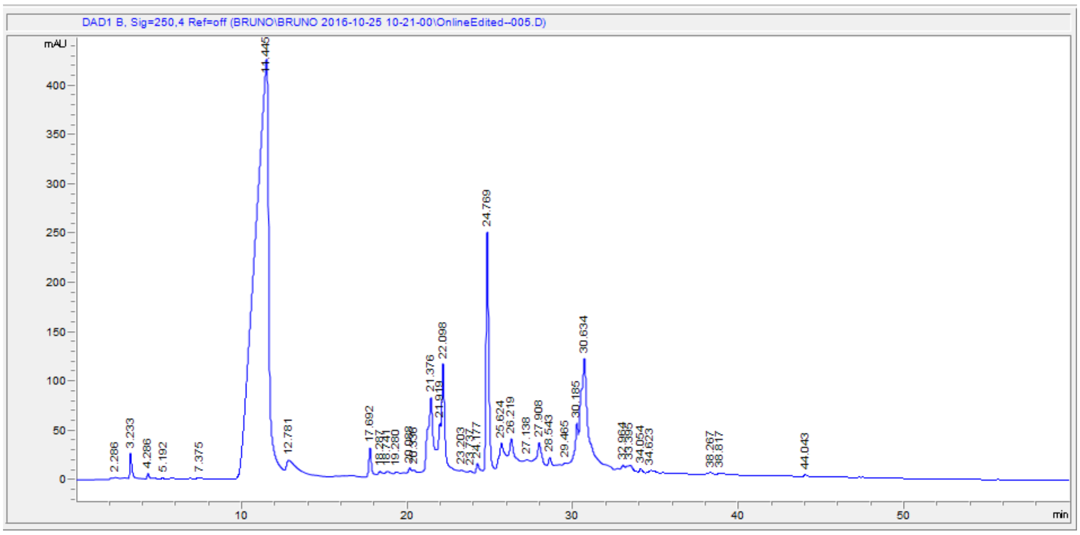

Fig. 5. A high-pressure liquid chromatography mass spectrum of an irradiated adenine — deoxyribose — formamide — NWA1465 mixture.

Table 2. Adenine — ribose reactions. FA = NH_2CHO; NWA 1465 is a specific meteorite designation.

№	Conditions	Adenine[a] (%)	Reaction product yield (%)[c]		
			α-pA	β-fA	α-fA (10) + β-pA
1	Dry[b]	75	7.3	2.9	14.8
2	FA	63	10.4	5.6	21.2
3	FA / NWA 1465	52	6.1	20.1	16.9

In the course of the reaction, furanosides (f) and pyranosides (p) are produced; they have the α- and β-isomere structure, respectively. α-fA = α-D-ribofuranosyl adenine; β-fA = β -D ribofuranosyl adenine; α-pA = α-D-ribopyranosyl adenine; β-pA = β-D- ribopyranosyl adenine. [a]Unreacted adenine. [b]Obtained by ribose dissolution in distilled water followed by drying. [c]Yield is calculated as the proportion (%) of nucleoside (mmol) to original adenine. The data are the mean results of three experiments with standard deviation not greater than 0.1%.

In 2018, a number of experiments on abiotic phosphorylation of nucleosides were conducted. This subject is a serious obstacle to research on the formation of the first living organisms. An optimal pathway was deduced of the synthesis of adenosine nucleotides from adenosine ($C_{10}H_{13}N_5O_4$) and sodium dihydrogen phosphate (NaH_2PO_4) under exposure to 170 MeV protons in the presence of the matter of the NWA 2828 carbonaceous chondrite meteorite as a catalyst. As a result, besides the target nucleoside, found in the mixture were its derivatives, adenosine polyphosphates and inorganic polyphosphates, which underscores the system's high reactivity. These experiments reproduce, to some extent, the conditions in space or on the early Earth, when solar wind protons not only passed through interplanetary space but also reached Earth's surface. The experiments thus allow modeling a prebiotic phosphorylation scenario. Adenosine1 phosphorylation was performed under four different experiment conditions (see the caption of Fig. 6).

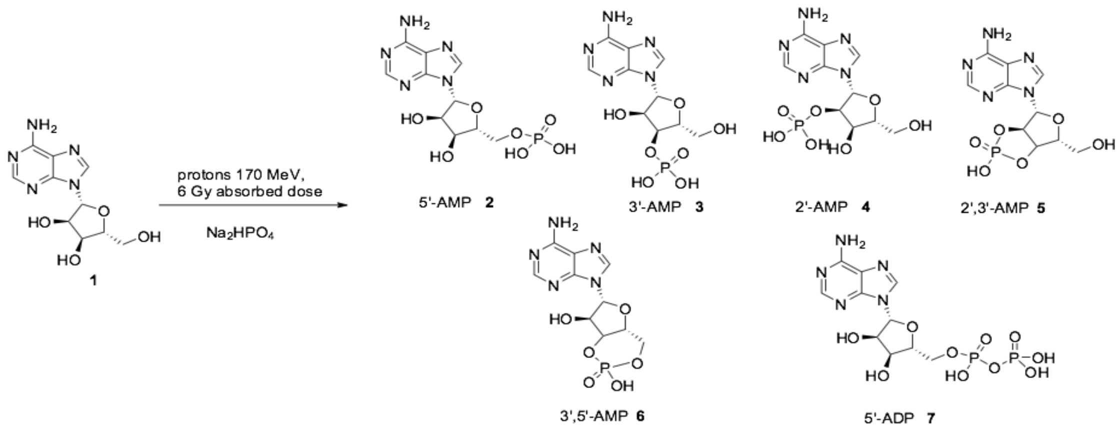

Fig. 6. Adenosine nucleotides (2–7) obtained by irradiation of adenosine (1) and NaH_2PO_4 by 170 MeV protons under the following four experiment conditions: (A) dry powder mixture of adenosine and NaH_2PO_4; (B) dry powder mixture of adenosine, NaH_2PO_4, and NWA 2828; (C) adenosine and NaH_2PO_4 in a liquid NH_2CHO solution; (D) adenosine powder, NaH_2PO_4, and NWA 2828 in a liquid NH_2CHO solution.

In all four reaction mixtures, formation was observed of alicyclic and cyclic adenosine nucleotides (Fig. 28): 5'-adenosine monophosphate (5'-AMP) (2), 3'- adenosine monophosphate (3'-AMP) (3), 2'- adenosine monophosphate (2'-AMP) (4), and 2', 3'-cyclo-adenosine monophosphate (2', 3'-cAMP) (5). In addition, a significant yield of adenine was observed, which formed due to a partial break of the β-glycosidic bond. Also, 3', 5'-cyclo-adenosine monophosphate (3', 5'-cAMP) (6) and 5'- adenosine diphosphate (5'-ADP) (7) were obtained in the (B) and (D) reactions. It was established in the experiments that the total yield of adenosine nucleotides significantly increased when the reaction mixture contained formamide (NH_2CHO) and meteorite matter. The results of this research have been submitted to *Chemistry — a European Journal*, 2019.

3. *Biogeochemical studies of cosmic dust*

M.V. Frontasyeva *et al.* [16,17] studied in 2018 cosmic dust from moss samples collected in Belarus, Georgia, Russia, and the U.S. Microanalysis showed that the samples contained clastic, anthropogenic, and cosmic dust particles. The latter consisted most often of Fe, Fe-Ni, and Fe-Cr minerals.

Compared with Arctic ice, Antarctic ice contains much less terrestrial and no anthropogenic dust. S.A. Bulat *et al.* [18,19] performed in 2018 a cycle of studies to search for cosmic dust particles in Antarctic ice. Found were iron-stone micrometeorites, but no carbonaceous chondrites.

4. Cosmic matter research with nuclear physics methods

M.V. Frontasyeva *et al.* (Laboratory of Neutron Physics, JINR) have performed at the IBR-2 reactor neutron activation analysis of cosmic dust particles. Samples were collected in Belarus, Georgia, Russia, and the U.S.

Most of the particles, when passing through the atmosphere, are subject to melting. It is especially typical of larger particles. Cosmic spherules have been observed; these particles are relatively easy to identify. They are the background magnetic component of cosmic dust. In the latter, Fe, Fe-Ni, and Fe-Cr minerals have been found most often.

Organizational activities

- A chemical laboratory has been created.
- An atlas of Orgueil meteorite microfossils has been prepared.
- The makeup of Dubna University's astrobiology textbook has been done.

Results expected in 2020–2022

Research will be continued in all the fields listed above. Estimation will be continued of the total amount of cosmic matter falling on all Earth's surface (tons a year); data will be obtained on the dynamics of cosmic dust (CD) fallout over a large territory. The following particle parameters will be determined: morphology, structure, distribution by size, and elemental, isotopic, and mineralogical composition. Also, changes of these parameters in time will be evaluated for different terrains and different time intervals. These studies will allow clearing up how much CD falls on Earth; its elemental and isotopic composition; and whether it has an organic component and if yes, what specifically.

In the course of this research, the following activities will be performed:

- Selection and preparation of meteorite and terrestrial rock samples.
- Further studies of meteorite and terrestrial rock samples using a Tescan Vega 3 scanning electron microscope (SEM) with an X-ray microanalyzer.
- Preparation of illustrated atlases of microfossils in carbonaceous chondrite meteorites.

The following equipment of the following collaborating institutions will be used: Tescan Vega 2 ZMU SEMs with an INCA Energy 450 system for energy dispersive X-ray microanalysis, CamScan systems with a Link-860 microanalyzer, and Zeiss systems with an analyzer of the Paleontological Institute RAS; a Tescan Vega 2 microprobe with add-ons for wave, energy dispersive, and cathodoluminescence analysis of Borok Geophysical Observatory (the Borok branch of the Institute of Earth Physics RAS); the scanning electron microscope of the Analytic Center at the RAS Geological Institute; and equipment of the RAS Institute of Ore Deposit Geology, Petrography, Mineralogy, and Geochemistry; RAS Institute of Space Research, etc.

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Cost evaluation

To develop the laboratory basis of the Astrobiology Sector of the LRB JINR and collect and analyze cosmic and terrestrial matter samples, about 130,000 USD will be required during three years. The costs include the construction and equipment of a block of clean and cold rooms, and the price of the laboratory instruments and expendable materials. The table below shows the cost breakdown by year in thousand USD.

	1st year	2nd year	3rd year
Year	2020	2021	2022
Equipment	40	30	30
Expendable materials	5	5	5
Payments for agreement-based scientific research work	-	-	-
Travel allowance	5	5	5
Total	**50**	**40**	**40**

Work schedule

2020

Expansion of the meteorite and terrestrial rock collection. Resupplying with equipment the chemical laboratory for studying the synthesis of complex prebiotic compounds from formamide. Analysis of prebiotic compounds and catalysts. Evaluation of the catalytic activity of terrestrial rocks. Work on the creation of an illustrated atlas of microfossils in the Murchison meteorite. Preparation of an experiment on studying the possibility of the synthesis of prebiotic compounds from a formamide — meteorite matter mixture in open space aboard the Bion-M spacecraft. Evaluation of the research results.

2021

Further cosmic dust collection; sample preparation and analysis. Identification and studies of microfossils and organic matter in meteorites and the most ancient terrestrial rocks. Analysis of prebiotic compounds and clearing up the catalysts' nature. Publication of an illustrated atlas of microfossils in the Murchison meteorite.

2022

Research on extremophiles, the underground biosphere, weathering rinds, the cryolitic zone, meteorite matter, and cosmic dust.