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REVIEW ARTICLE

Astrobiology in Russia: past, present and future prospects

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Abstract

The purpose of this review is to examine the historical background and the scientific and philosophical foundations underlying the emergence and development of Russian astrobiology. In addition, it seeks to provide the

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international scientific community with a comprehensive account of the principal achievements of the Russian scientists whose research has contributed to the field of astrobiology. Their contributions include experimental models of prebiotic synthesis and impact-generated organics; the formulation of original theories of life's origin; investigation of cold and glacial terrestrial ecosystems as analogs for Mars and celestial icy bodies; advances in bacterial paleontology with significant astrobiological implications. A significant amount of data produced by Soviet scientists were published exclusively in Russian journals and therefore remained largely inaccessible to the international scientific community. The review also discusses the current state and principal scientific directions of Russian astrobiology, its international cooperation, the challenges and prospects it faces, and provides a comparative analysis with the development of astrobiology in Western countries. Its primary aim is to outline the fundamental structure of astrobiology research in Russia from a retrospective perspective.

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Introduction

Astrobiology has a long history in Russia. Its formation was significantly influenced by both the outstanding achievements of world science in the late 19th and early 20th centuries, and the progressive scientific and philosophical ideas, which united their representatives within the framework of the doctrine of cosmism. Subsequently, in the Soviet Union, active research pertaining to space exploration, manned space flight programs and space missions to Venus and Mars marked the beginning of active data collection and the transition from theoretical and remote to the real practical study of space and cosmic bodies.

Currently, Russian astrobiology is developing in various directions, the priority of which are determined by historical, technological and geographical factors. Russia, with its advancements in

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theoretical and experimental developments in space studies, is adequately capable of making a significant contribution to the development of world astrobiology collectively. The collective participation of their scientists in astrobiology projects promotes closer cooperation and integration of other related scientific groups within the framework of achieving common goals. This is ultimately one of the main principles of the development of astrobiology, reflecting the basic philosophies of the universality and integrity of our world, which prevails in the debates of philosophers-cosmists.

This review presents significant achievements of Russian astrobiologists. They include important contributions in concepts of origin of life and its evolution; studies of biodiversity of various extreme ecosystems and modeling hypothetical habitability of extraterrestrial icy worlds; and investigation of microfossils as well as a variety of experiments on the orbital spacecrafts.

This is the first comprehensive retrospective review of astrobiological research in Russia which can serve as (i) the basis for uniting the Russian astrobiological community; (ii) the systematic organization of data accumulated over the past three quarters of a century of research; and (iii) the presentation of the state-of-the art of Russian astrobiology for national and international scientific collaborations.

Formation of ideas about the relationship between terrestrial phenomena and space

In Russia, the ideas of "cosmists" have had a significant influence on the formation of plethora of scientific concepts in the field of space exploration and the potentially possible proliferation of life in the Universe. Notions about the cosmos as a single structural entity – living organism – date back to ancient philosophy, in particular to the teachings of Plato (Briot, 2012; Nascimento-Dias and Martinez-Frias, 2023; Noack *et al*., 2015). The term "cosmism" comes from the Greek word "cosmos" meaning "ordered world."

During the Late Middle Ages, one of the exponents of a general philosophical view on the prevalence of life beyond the Earth was Giordano Bruno in his work "On Infinity, the Universe and the Worlds" (1584). Subsequently, concepts of evolutionary development applied to the Universe as a whole began to be examined and formalized within Western scientific thought during the latter half of the nineteenth century and the early decades of the twentieth.

Alexander von Humboldt's five-volume work "Cosmos" (1845–1859), the foundation of German philosophical cosmism, had an immense influence on both European and Russian cultures. In France, this was developed further by Henri-Louis Bergson who noted in "Creative Evolution" (1907). The American version of "cosmic philosophy" was presented in the works of the religious naturalist John Fiske (the term – "Philosophy of Cosmism", 1874) and in the works of Samuel Alexander (1920); in addition, a number of other scientists reworked the notion in the form of "emergent evolution," emphasizing the qualitative uniqueness of each new level of evolution.

Russian cosmism arose as a generalization of the most striking views of foreign thinkers and Russia's own ideas which formed into an independent deep scientific and philosophical direction pillar. Scientist and philosopher-cosmists sought to prove the systematic nature of the laws of the origin and development of life and their relationship with the general laws of the universe. The most important feature of cosmism at that time was the study of rapidly developing sciences and their integration into a universal cosmic science of life, which evolved into the new field of astrobiology. The latter science is now characterized by the same multidisciplinary approach.

The beginning of the 20th century witnessed an unprecedented acceleration of scientific and technological progress. Simultaneously, art, philosophy, and science mutually influenced one another, while probing living organisms' essence and their connection to the environment.

The spiritual and philosophical direction of Russian cosmism can be seen in the works of the famous Russian thinkers N.F. Fedorov, V.S. Solovyov, N.A. Berdyaev, P.A. Florensky and others. Philosophers believed that through rational activity, humans have a special mandate to harness nature's forces and shape the future – a mission that requires comprehending the world and its universal laws.

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N. F. Fedorov said that "the earth is open on all sides, and the means of transportation and modes of life in different environments not only can, but should change" and believed that "in regulation, in managing the forces of blind nature lies that great work that can and should become common" (1906).

The scientific and philosophical ideas of Russian cosmism formed the basis of the work of many artists, painters, writers, and poets. Then, art "uncorked the human imagination and made it possible to think beyond the limitations of existing scientific approaches and methods", to elevate above the ordinary and often anticipated future scientific discoveries which largely influenced the development of science (Gacheva, 2004).

As V. I. Vernadsky wrote in his personal correspondence: "We know only a small part of nature, only a small part of this incomprehensible, unclear, all-encompassing mystery. And everything we know, we know thanks to the dreams of dreamers, visionaries and scientist-poets; every step forward was made by them."

A wonderful confirmation of this precept is the work of K.E. Tsiolkovsky. Many tenets of this scientist and thinker, who founded modern cosmonautics, first appeared in his science fiction works titled: "Beyond the Earth. Dreams of the Earth and the Sky and the Effects of Universal Gravitation" (1895); "On the Moon" (1893); and "The Adventures of the Atom" (1919).

It is also necessary to mention science fiction books by: Alexei Tolstoy's "Aelita" was about a flight to Mars, the first edition of which was published back in 1923; a novel by A.R. Belyaev entitled: "The Star of KETs" (1936), which sets out the ideas of K.E. Tsiolkovsky about the activities of people beyond our Earth and "The Andromeda Nebula" (1957), by I. Efremov was about interstellar travel.

In the context of cosmism, the famed triad – Dream (Fantasy), Theory, Implementation – was most clearly evident, for without it the development of civilization would be impossible (Zeleny, 2022). Art, philosophy, and science evolved in concert, each enriching the others with new ideas and perspectives.

The scientific and philosophical concepts of Russian cosmism formed the basis of the work of many painters (M.K. Čiurlionis, K.S. Malevich, V.V. Kandinsky, K.F. Yuon, P.N. Filonov, N.K. Roerich, and the Armavella group), who embodied the notions of an inseparable and multifaceted relationship between the macrocosm and the microcosm in their paintings (Figure 1).

The painter Pavel Filonov understood the meaning of his work in reflecting the unity of science and art, emphasizing that life is not static but is evolving continuously. To describe his works, he invented new terms that other artists had never envisioned previously and these terms are biomonism, biodynamics, emanation, and genesis.

Scientific and philosophical views and concepts of Russian scientists-cosmists and the emergence of astrobiology

In the natural sciences, researchers examined and investigated the relationship between life, humanity, and space (see Table 1), placing special emphasis on the scientific achievements that substantiate this connection.

M. V. Lomonosov was among the first to articulate the idea that outer space forms an extension of life on Earth and that the laws of nature operate uniformly throughout the cosmos. He may therefore be regarded as the founder of Russian cosmism. His works in the eighteenth century introduced the concept of other worlds into Russian intellectual culture, where it subsequently began to receive serious consideration. In his doctrine, later termed "Physical Theology," Lomonosov emphasized the centrality of scientific inquiry in elucidating the nature of the world (Zeleny, 2022).

In the late 19th to early 20th centuries, natural science cosmism gained further significant development in the works of the renowned Russian scientist K.E. Tsiolkovsky, who had a huge influence on the subsequent organization of space research and proposed the notion of life spreading further afield in space. In his numerous works, the key propositions being: "Living Creatures in Space" (1895), "The Living Universe" (1923) and "Cosmic Philosophy" (1935). He developed his ideas

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Figure 1. *A proposition of cosmos without emptiness (biocosmos) in the painting "Symphony of the Cosmos" (1925) by A.P. Sardan, Armavella group.*

relating life as a universal phenomenon, the connection of living organisms with cosmic phenomena and the inevitability of life spreading elsewhere in space.

A great contribution to the development of the cosmism doctrine and the study of natural phenomena was forwarded by the Russian physicist N.A. Umov, who introduced the theory of the "Negentropic Essence of Life," which resisted the ability to decay by increasing the level of organization. He attached great importance to the philosophical understanding of physics. It should be noted that he is one of the founders of modern biophysics (Tverdislov, 2013). Umov proposed that there is no contradiction between animate and inanimate nature, and that we must strive to discern the general laws governing both.

Of great importance for the evolution of the scientific advancement of cosmism were the works of A.L. Chizhevsky, the founder of heliobiology – the science of the relationship between living organisms, solar activity and other cosmic influences. He proposed a bold hypothesis highlighting the connection between solar activity and outbreaks of epidemics ("Epidemic Catastrophes and Periodic Activity of the Sun," 1930) and the influence of solar cycles on the behavior of society and the historical process ("Physical Factors of the Historical Process," 1924). Chizhevsky reflected deeply on the unity of all phenomena in the Universe and adopted a synthetic approach, seeking to integrate diverse

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Table 1. *Scientific and philosophical contribution of Soviet and Russian scientists to the development of astrobiology*

Name	Date	Scientific contributions and main publications
Tsiolkovsky K.E.	1895–1935	"Space Philosophy and Theoretical Issues of Cosmonautics"
	1895	"Living Creatures in Space"
	1923	"Living Universe"
	1925	"Monism of the Universe"
	1935	"Space Philosophy"
Umov N.A.	1902	"The Concept of the Anti-entropic Essence of Life"
	1916	Collected works of Professor Nikolai Alekseevich Umov
Chizhevsky A.L.	1915–1930	Heliobiology
	1924	"Physical factors of the historical process"
	1926	"Cosmic radiation as a biological factor. The result of experimental studies on the influence of cosmic radiation - solar and stellar - on cells and tissues"
	1930	"Epidemic catastrophes and periodic activity of the Sun"
Oparin A.I.	1924–1977	"Theory of the Origin of life (primordial soup, coacervates)"
	1924	"The Origin of life"
Vernadsky V.I.	1926–1940	The doctrine of the biosphere. The concept of transformation of the geosphere by living organisms. Biogeochemistry.
	1926	"The Biosphere"
	1931	"On the Conditions of the Emergence of life on Earth"
	1940	"Biogeochemical essays"
Kholodny N.G.	1944	"Anthropocosmism"
	1947	"Thoughts of a Naturalist on Nature and Man"
Efremov I.A.	1950	"Taphonomy and the Geological Record"
Tikhov G.A.	1941–1953	Astrophysical Research of Mars
	1945	Term "Astrobotany"
	1949	Book "Astrobotany"
	1951	Term "Astrobiology"
	1953	Book "Astrobiology"

scientific disciplines and methods across both the natural sciences and the humanities. He was one of the first in the world to have begun the investigative research in the field of space biology. His article "Cosmic radiation as a biological factor. The result of experimental research on the effect of cosmic radiation – solar and stellar – on cells and tissues" was published in 1929, though only in France.

The teachings of V.I. Vernadsky had a huge influence on the scientific and philosophical understanding of the organization of the living world and, in particular, on the development of astrobiology, which later became a new science in its own right (Marov, 2013). He developed the concept of the biosphere, defined life as a cosmic phenomenon and noted the decisive influence of life processes on the geology of the planet, highlighting their immense transformative potential. He further proposed that humanity's transition to autotrophy represents a fundamentally new and highly promising mode of compound exchange with the environment. Vernadsky's most important scientific contribution was also the creation of the biosphere doctrine as well as the important transformative nature of life on the planet. The main provisions of this concept were formulated between 1916 to 1926. The recognition of biogeochemical energy within living matter, together with the identification of the biogeochemical functions of life, led scientists to conclude that living matter constitutes the most powerful geological force – one that has shaped, and continues to shape, the Earth's present form. It has been instrumental in shaping the Earth's geomorphic evolution and continues to exert a primary influence on the planet's

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Figure 2. *Illustration and text excerpt standing for "The New Science. Astrobiology" from the magazine "Science and Life" (1951), where G.A. Tikhov first announced the creation of a new science of astrobiology.*

contemporary geochemical and geophysical configuration. Based on his theory of the biosphere, Vernadsky not only initiated new advancements at the intersection of sciences, such as geochemistry and biogeochemistry, but also astrochemistry and radiochemistry (Marov, 2013).

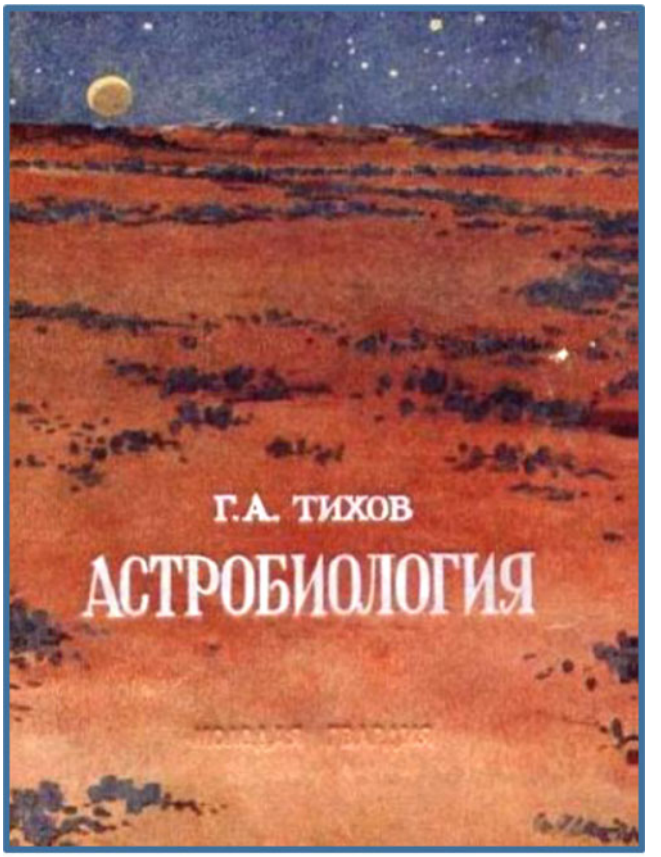
Within the scientific arena, a special place belongs to A.I. Oparin, who proposed a biochemical hypothesis of the origin of life. According to Oparin, the initial step of abiogenic synthesis of organic compounds occurred in the reduced atmosphere of the ancient Earth. The gradual accumulation of the organic compounds in the ancient ocean led to the formation of the so-called "primordial soup." As a result of polymerization, complex organic compounds such as peptides, lipids, nucleic acids would have been gradually formed – leading to the development of "coacervates": these also were able to grow in size in the watery environments of the ancient Earth. Combining coacervates with nucleic acids led to the formation of primitive self-reproducing living entities, possibly probionts. These represented prototypes of the earliest living unicellular organisms. Subsequently, several stages in the formation of both simple and complex organic compounds were experimentally validated in the pioneering studies of S. Miller, J. Oro, L. Orgel, S. Akabori, and others (Akabori *et al*., 1956; Lohrmann and Orgel, 1968; Miller, 1953; Oró, 1963). Oparin (1976) emphasized that the problem of life's origin carried significance not only for science but also possessed profound philosophical implications. He said: "This is one of the most important worldview problems of humanity, in which, as if in focus, all scientific knowledge is collected." His hypothesis had a huge impact on the development of astrobiology and was included in biology textbooks as a classic concept of how Earth's first living organisms may have arisen. Oparin himself considered his theory in a broader context. He wrote: "At present, the hypothesis pertaining to the origin of life is not only the foundation for the new science of "theoretical biology." The science revealed the essence of life and research in evolutionary biochemistry; a theoretical basis for cosmochemical research and the search for life on various celestial bodies" (Oparin, 1975).

In his anthropocosmism, N. G. Kholodny regarded humanity as one organic part of the world, and held that natural scientific knowledge is the key to understanding our place in nature and our relationship with the cosmos.

The notions of cosmism were also contained in the work of the writer and paleontologist I.A. Efremov, who instigated the science of taphonomy (the study of fossil distribution which enables researchers to reconstruct the functioning of ancient biocenoses and past ecosystem) at the intersection between geology and paleontology. Thus, recognizing the inseparable unity of all sciences and the relevance for interdisciplinary research.

However, a significant event in the history of the study of extraterrestrial life was the scientific work of academician G.A. Tikhov (Cockel, 2024), who, while studying the possibility of the existence of vegetation on Mars, first introduced the term "astrobotany" in 1945, and then the term "astrobiology" in 1951 (Figure 2).

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Figure 3. *The first book on astrobiology, published by A.G. Tikhov in 1953, "Molodaya Gvardiya" Publishing House, Moscow.*

> *. . . life is an extremely persistent and stubborn phenomenon. It can exist in conditions that are very different from those on Earth. Life can and should exist not only on the planets of the solar system, but also on planets that undoubtedly move around the countless stars found in the infinite Universe" G.A. Tikhov, Corresponding Member of the USSR Academy of Sciences*

Tikhov authored the pioneering works Astrobotany (1949) and Astrobiology (1953), in which he articulated the foundational scientific frameworks of these emerging disciplines, thereby marking the inception of a rapidly developing field (Figure 3). In his works, Tikhov expounded notions relating to the extremely high adaptability of life under various unfavorable conditions on distant planets and, in essence, substantiated the importance of studying extremophiles as model organisms in the context of astrobiology.

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It should be noted that A.A. Sternfeld, a Russian scientist of Polish descent, was perhaps the first scientist who used the term astrobiology in a scientific paper published in an international scientific French journal, in which he described the new science, the main goal of which could be to assess the habitability of other worlds (Briot, 2012; Nascimento-Dias and Martinez-Frias, 2023; Sternfeld, 1935). However, it was Tikhov who truly first used this term within the Russian scientific community. In addition to the term astrobiology, at that time the terms cosmobiology, exobiology, bioastronomy also appeared, but it was the term astrobiology that finally became established in the scientific community (Heizer and Nascimento-Dias, 2023).

In 1947, Gavriil Tikhov created the world's first Astrobotany Department, at the Academy of Sciences of Kazakh SSR, initiating systematic research into the possibility of life on other planets. Subsequently, Tikhov and this emerging scientific discipline faced intense criticism. In 1952, the Presidium of the Academy of Sciences of the Kazakh SSR organized a broad discussion to critically discuss the work of the department and its research into extraterrestrial life. Opponents believed that all of Tikhov's ideas were a big mistake. It is known that at the same time, the well-established American astronomer Albert Wilson came to Kazakhstan to visit Tikhov. He highly praised Tikhov's research and was very interested in his ideas. Wilson said: "America recognized Tsiolkovsky too late, and now we are correcting the mistake by recognizing Tikhov's ideas." Soon after his trip to Kazakhstan, Wilson organized the world's first seminar on Astrobiology in the United States of America. In the Soviet Union, after the death of Gavriil Tikhov in 1960, the Astrobotany Department was disbanded.

Main directions of modern Russian astrobiology

The second half of the 20th century was characterized and defined by revolutionary advances in biology, beginning with the discovery of the DNA structure by Watson and Crick (1953) and the subsequent rapid development of molecular biological techniques that made it possible to reconstruct phylogenetic relationships between all living organisms and study their diversity and distribution in various ecosystems at the genomic level. At the same time, the era of space exploration of near-Earth space began with the advent of rocketry engineering leading to exploration using spacecrafts. The first spacecraft that carried a living creature, namely a dog named Laika, was sent into outer space in 1957, followed by the first cosmonaut, Yuri Gagarin, who orbited the Earth in 1961. Subsequent to these two missions, it became possible for the first time to study the impact of space factors on various terrestrial organisms. Individually and independently, both the United States of America and the Soviet Union regularly launched space missions to planets in our Solar System. As part of the USSR space programs, unmanned spacecrafts successfully landed on the surface of the Moon (Luna-9, 1966), Venus (Venera-7, 1970) and Mars (Mars-3, 1971). The active development of various natural science areas and the improvement of the methodological apparatus led to the accumulation of a large amount of new data, including data relevant to astrobiology. New concepts and new research areas emerged, to which Soviet/Russian scientists made a significant contribution – this continues to this day. Table 2 presents the names and achievements of Russian scientists who played pivotal roles in shaping the modern advancements of Russian astrobiology.

The scientific contribution of these scientists, along with those of other researchers, are outlined in the relevant sections below, each of which addresses specific areas of Russian astrobiology.

Unresolved research issues in astrobiology and related fields in Russia are addressed through three independent conferences, held regularly at the following institutions: the Institute of Physical-Chemical and Biological Problems of Soil Science of the Russian Academy of Sciences in Pushchino (IPCBS RAS), the Space Research Institute of the Russian Academy of Sciences in Moscow (IKI RAS), and the Joint Institute for Nuclear Research (JINR) in Dubna. Each conference has distinctive features shaped by the nature of its audience. Nevertheless, a generalized analysis of the astrobiology research presented across these meetings makes it possible to evaluate the structure of contemporary astrobiology directions in Russia (Figure 4).

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Table 2. *Main conceptual achievements of Soviet and Russian scientists in global astrobiology at the present stage*

Names	Date	Scientific contributions
Spirin A.S. and Belozersky A.N.	1959–2005	Development of the RNA World hypothesis.
Shklovsky I.S.	1960–1975	Creation of Soviet and Russian SETI.
Abyzov S.S.	1974–2001	Microbiological studies of Antarctic ice
	1978	Ultra-long anabiosis in microorganisms.
Gilichinsky D.A.	1978–2012	Study of ice ecosystems.
Zavarzin G.A. and colleagues	1984	The role of microorganisms in the functioning
	1993	and evolution of the biosphere.
	1995–2004	Models of primordial microbial communities of Earth – the hypothesis of the "soda continent."
		Principles of the evolution of biological systems.
		The theory of additive evolution.
		The concept of "Microbial community first".
Bonch-Osmolovskaya E.A. and colleagues	1988–present	Microbiological study of hydrothermal ecosystems, description of novel chemosynthetic processes.
Goldansky V.I.	1997	The role of chirality in prebiological evolution.
Rozanov A.Y. and Zavarzin G.A.	1997	Study of microbial fossils and bacterial paleontology.
Galimov E.M.	2001–2009	Development of the theory of sequential ordering.
Marov M.Ya.	2005–2015	Geochemical approach to the origin of life.
Mulkidjanian A.Y., Bychkov A.Yu., Koonin E.V. and colleagues	2012	Proposal of the origin of first cells at terrestrial, anoxic geothermal fields.

The analysis indicates that the primary themes of study in Russian astrobiology are cold and extremely cold ecosystems, particularly the icy regions of the Arctic and Antarctic. This focus reflects the geographical nature of Russia landscape, with its extensive cold climates and widespread permafrost zones. It should be noted that the study of extraterrestrial ecosystems includes a large share of work related to the survival of microorganisms in the Martian climate, which also mirror the above-mentioned cold environments as model ecosystems.

A substantial portion of priority astrobiology research in Russia is linked to astronomical studies and experiments conducted aboard orbital space stations, reflecting the country's status as one of the world's leading space powers.

Finally, a significant part of theoretical and experimental research is related to various aspects of the challenges of the origin of life, which is a continuation of the conceptual legacy of Oparin.

In more detail, the structure of various divisions of astrobiology in Russia and their interrelationships are shown in Figure 5. The interdisciplinary connections in the diagram are formed through current scientific interactions between scientists working in these scientific fields.

In fact, the real inter-relationships of such divisions and subdivisions are even more complicated. For example, the study of terrestrial extreme ecosystems as analogs of hypothetical extraterrestrial systems is important for organizing astrobiology experiments within the framework of missions to other celestial bodies. Concomitantly, new data on the study of physical and chemical conditions on individual celestial bodies in the Solar System encourages astrobiologists to search for new terrestrial organisms as possible candidates for survival in the extreme environments.

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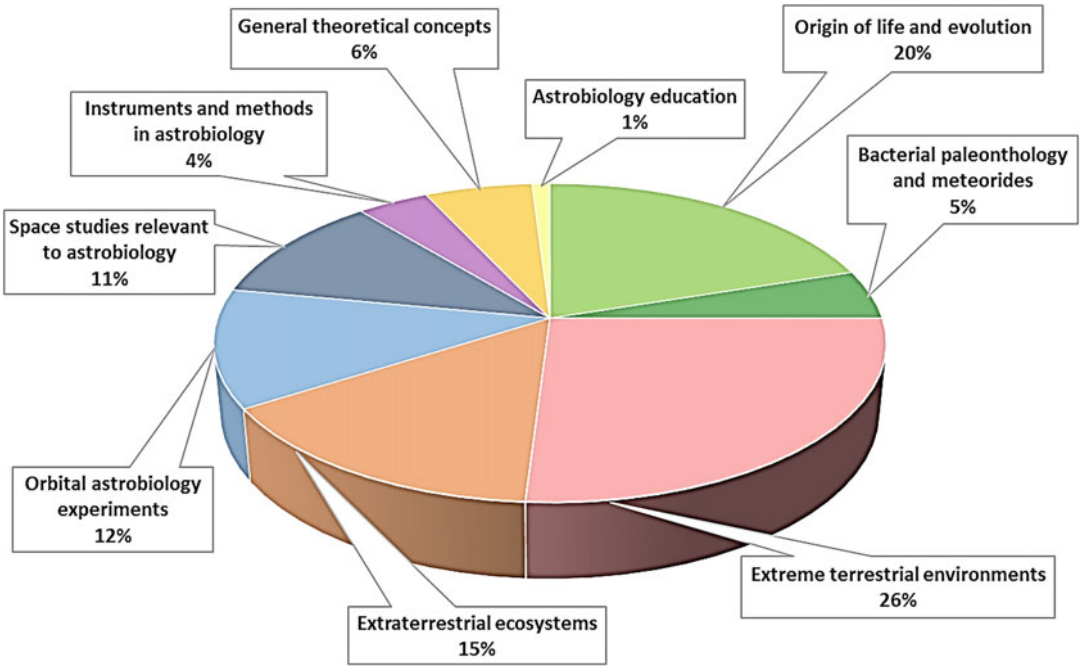


Figure 4. *The proportion of different astrobiology directions in Russia, calculated from the number of presentations given at the three conferences in Pushchino, Moscow and Dubna.*

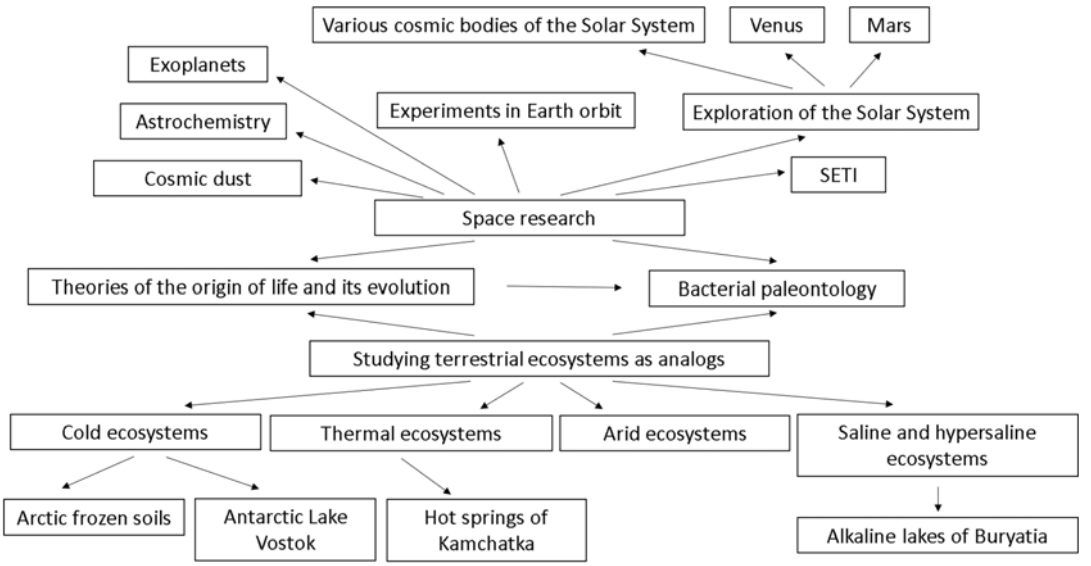


Figure 5. *Structure of the main divisions of astrobiology in Russia.*

Origin of life

Oparin was an active researcher throughout his life, developing and generalizing his hypothesis of the biochemical origin of life (Oparin, 1975, 1976). Together with a number of other scientists, he participated in the setting up of the International Society for the Study of the Origin of Life – The

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International Astrobiology Society (ISSOL) (Raulin-Cerceau, 2016), meetings of which are still held in a triennial cycle. Oparin's former student Mikhail Kritsky, who later headed his laboratory of evolutionary biochemistry at the A.N. Bakh Institute of Biochemistry at the Russian Academy of Sciences, together with his colleagues continued to develop the thesis of phase-separated microsystems (Kolesnikov *et al*., 2008) and study the abiogenic synthesis of molecules necessary for living organisms. He pointed out the importance of photochemical processes in the prebiotic accumulation of organic molecules important in the context of the origin of life (Kritsky *et al*., 1996, 1998, 2007, 2013) and postulated an important role of coenzymes as catalysts in the RNA world (Kritsky *et al*., 2004).

The works of Ilya Prigogine, a famous Belgian physical chemist (born into a Russian-Jewish family in Moscow) on the thermodynamics of non-equilibrium processes and dissipative structures, had a very great influence on the understanding of the processes of self-organization and development of biological systems (Prigogine, 1955). The theory of dissipative structures describes the process of internal self-reorganization that occurs in open systems that exchange energy and matter with the environment. According to this theory, open systems can create new structures *de novo* during the initial state of the system. These structures arise due to the process of dissipation of energy, which is dispersed into the environment (Prigogine and Lefever, 1973). This concept considered the emergence and evolution of life as self-reorganization in non-equilibrium processes and was enthusiastically accepted by the world scientific community (Prigogine and Nicolis, 1977*)*. Within his long collaboration with Moscow State University (MSU), Prigogine inspired and helped to organize the Institute of Complex Systems Mathematical Research (IMISS of MSU) in 1995. Its primary objective was to advance Prigogine's ideas on developing a theory of non-equilibrium systems, within the framework of broad international cooperation led by the International Solvay Institutes for Physics and Chemistry. Over time, research on modeling the behavior of biological non-equilibrium systems became increasingly important at IMISS. This effort culminated in the long-term IMISS-1 experiment, which recorded and analyzed accelerations during orbital flight aboard the Lomonosov satellite launched in 2016. The study had a significant impact on biophysics and human physiology in space, particularly in relation to the phenomenon of "space motion sickness" (Sadovnichii *et al*., 2018). Prigogine's work most notably earned him the 1977 Nobel Prize in Chemistry "for his contributions to non-equilibrium thermodynamics, particularly the theory of dissipative structures."

A.S. Spirin, a famous Soviet and Russian molecular biologist and one of the architects of the "RNA world" hypothesis, made a huge contribution to the origin of life. Spirin was a student of A.N. Belozersky, who was the first to point out the possible primacy of RNA in the origin and early development of life (Belozersky, 1957, 1959). Together with Belozersky, Spirin published a paper in which he reported that the main part of RNA is not involved in the transfer of genetic information, but instead plays a different role. In 1960, Spirin first isolated ribosomes and began a series of studies on their spatial organization (Spirin, 1960). Spirin suggested that abiogenically synthesized oligoribonucleotides actively recombined through the mechanism of spontaneous non-enzymatic transesterification, leading to the formation of elongated RNA chains and giving rise to their diversity. It was in this way that both catalytically active types of RNA (ribozymes) and other types of RNA with specialized functions could have appeared in the population of oligonucleotides and polynucleotides (Spirin, 2001) (Figure 6).

The appearance of such ribozymes in a small body of water could have become the basis for the preservation and development of the "RNA world" on ancient Earth (Spirin, 2005). According to Spirin, an important condition for development is the compartmentalization of the system. In the case of the RNA world hypothesis, this could have been possible in molecular "colonies" of RNA, the formation of which was proven in the works of A.B. Chetverin's group. The essence of this phenomenon is that, when appropriate conditions are met, RNA replicates in a cell-free system to form colonies similar to growing colonies of microbial cells. Such colonies may well undergo recombination reactions and rearranges their nucleotide sequences (Chetverin and Spirin, 1995; Chetverin *et al*., 1997; Munishkin *et al*., 1991). It is highly probable that these RNA colonies may satisfy most of the requirements for a "universal precursor" of living entities on Earth (Woese, 1998): a high level of mutations due to imperfect mechanisms of replication of genetic material, free exchange of genetic material between

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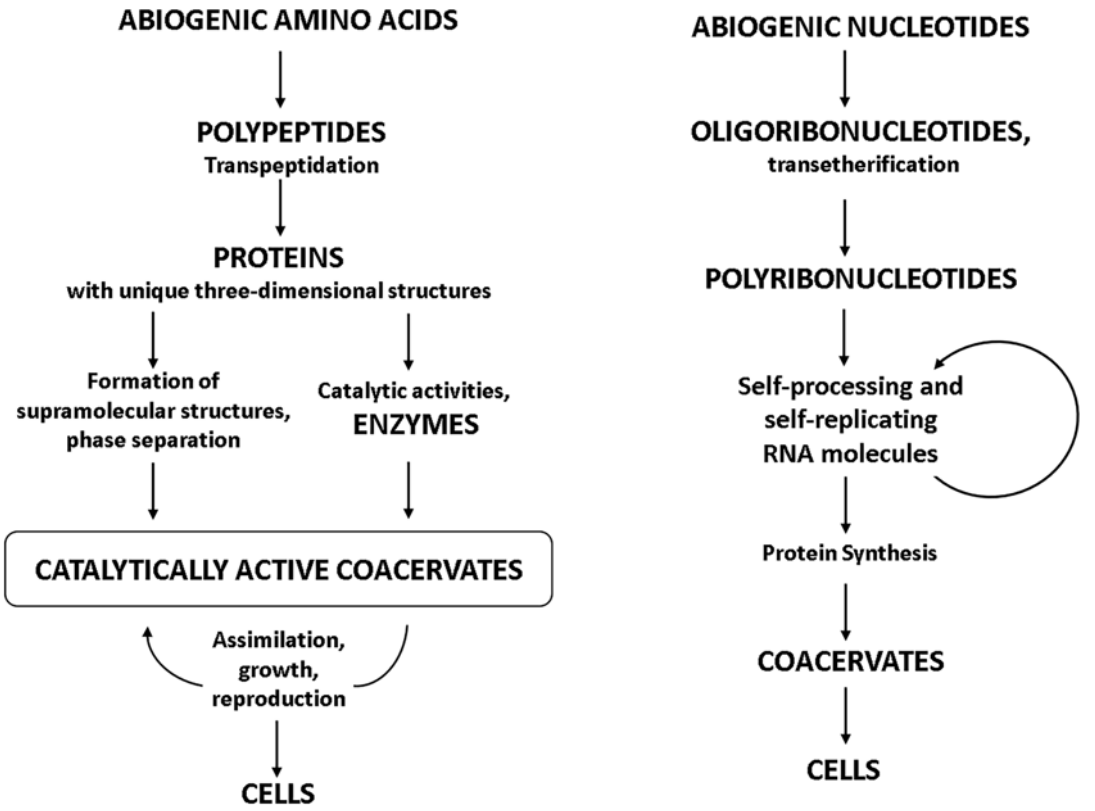


Figure 6. *Comparison of the origins of life according to the protein-coacervate theory of A.I. Oparin (left) and the RNA world developed by A.S. Spirin (modified from Spirin, 2001). The "RNA first" theory has replaced the "protein first" theory and is currently one of the most widely accepted theories of the origin of life in the world.*

progenotes, and a communal mode of life – when any products and innovations arising *de novo* become the property of all (Spirin, 2005a, 2005b, 2010). Such a commune had to evolve very quickly. Anyhow, the entire evolutionary path to the formation of cellular microorganisms including its supporting infrastructures, DNA, and a modern protein synthesis apparatus was completed in less than half a billion years (Spirin, 2005). Spirin also postulated the emergence of a molecular machine during the RNA world – a replicating ribozyme with a helicase function, capable of significantly increasing the rate of RNA replication (Spirin, 2004, 2013). Finally, Spirin identified the conditions for the emergence of a communal RNA world: (1) the presence of liquid water and RNA-adsorbing surfaces; (2) the implementation of cycles of drying and moistening (or wetting), heating and cooling, freezing and thawing; (3) protection from cosmic radiation, indicating that such processes could, in principle, occur both on Earth and on other cosmic bodies or even in comet nuclei (Spirin, 2007).

An alternative hypothesis for the origin of life, the theory of sequential ordering, was developed by the famous geochemist E. M. Galimov (Galimov, 2009b). He considered processes in which ordering is an attractor in accordance with Prigogine's theory (Prigogine, 1955) and assumed that life is a natural form of occurrence of this type of process, uniquely inherent in carbon chemistry (Galimov, 2001, 2004). Galimov believed that in primitive chemical systems, the specified mechanism is carried out with the participation of the adenosine triphosphate (ATP) molecule, which plays a special role in the origin and evolution of life. This is due to its universal ability to couple with polymerization reactions that underlie the synthesis of biologically important structures (Galimov, 2009).

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Another alternative to the RNA world is the progene hypothesis of the Russian virologist A.D. Altshtein, which suggests that the formation of the first bimolecular nucleoprotein genetic system (protoviroid), is considered as the first living organism *Protoviroidum primum* (Altshtein, 1987, 2015).

V.I. Goldanskii made a significant contribution to the problems of the origin of life in his works on the role of chirality during the prebiotic evolution. He suggested that the formation of complex organic molecules in cold interstellar dust should be considered as an important prehistory of life (Goldanskii, 1977). He also analyzed mechanisms of solid-phase astrochemistry reactions to find direct connections to the formation of organic compounds in space and their delivery onto Earth which contributed to prebiotic evolution (Goldanskii, 1997). Goldanskii postulated that the emergence of chiral purity of the basic "building blocks" of life – sugars and amino acids – occurred at the early stages of prebiological evolution and is a mandatory condition, without which the emergence of self-replication is impossible (Goldanskii and Kuzmin, 1991). In other words, chiral purity is the relic property that the biosphere inherited from the stages of chemical evolution of the organic environment on the primitive, prebiological Earth. Goldanskii (1993) examined mirror-symmetry breaking in both "warm" (terrestrial) and "cold" (extraterrestrial) origin-of-life scenarios. He concluded that deracemization occurs cooperatively through a bifurcation process, with the biosphere's chiral signature (L-amino acids, D-saccharides) representing a "memory" of a random bifurcation choice rather than a consequence of parity violation in weak interactions. Furthermore, he argued that cold, solid-phase astrochemical pathways are more promising than warm, terrestrial ones.

S.E. Shnol' used a thermodynamic approach in analyzing biological evolution from primary matrix molecules to higher biological forms and described the process of biological evolution as a sequential, alternating action of various physical and physicochemical criteria of natural selection. These factors come into play when their action becomes key. Shnol' introduced the concept of the "principle of ultimate perfection" for this, which is similar to the "limit transition method" popular in physics and mathematics (Shnol', 1973, 1979).

A. Mulkidjanian pointed out that the resistance of molecules to ultraviolet radiation may be an important factor in their selection at the stage of abiogenic synthesis (Mulkidjanian and Galperin, 2007). He also developed the theory of the "zinc world" – a scenario of abiogenic synthesis of organics at geothermal sources (Mulkidjanian, 2009; Mulkidjanian and Galperin, 2009; Mulkidjanian *et al*., 2025). Subsequently, leading representatives of the biochemical (Mulkidjanian), geochemical (A. Yu. Bychkov), and bioinformatic (E. V. Koonin) schools of Moscow State University – working collaboratively with research groups across Europe, the USA, and Russia – developed one of the most recent theories proposing that the earliest cells emerged within terrestrial, anoxic geothermal fields (Mulkidjanian *et al*., 2012). They reconstructed the "hatcheries" of the first cells by combining geochemical analysis with phylogenomic scrutiny of the inorganic ion requirements of universal components of modern cells. The analysis revealed that protocells must have evolved in habitats with a high K^+/Na^+ ratio and high concentrations of Zn, Mn, and phosphorous compounds. Modern viscous watery fluid in hot mud pools most closely resembles cellular cytoplasm, and life on Earth could have emerged – driven by UV-rich solar radiation – at photosynthetically active, porous edifices of hydrothermally precipitated zinc sulfide (ZnS), similar to those found around modern deep-sea hydrothermal vents. The ZnS surfaces served as templates for the synthesis of biopolymers by the solar radiation.

Koonin considered the probability of events leading to the complexity of systems in the context of the origin of life and its evolution based on comprehensive molecular evolution studies (Koonin, 2007, 2011).

A. Markov proposed the concepts of spontaneous polymerization of oligonucleotides on mineral matrices and non-enzymatic polymerization to solve the difficulty of prebiological RNA synthesis (Markov, 2015).

Kompanichenko V.N. proposed the concept of thermodynamic inversion (TI concept) for the origin of life on and possibly on other distant planets as well. This proposes that the transition of a non-living prebiotic system (organic microsystems and their cluster) into an initial living system (primary

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microorganisms and their population) is possible only through thermodynamic inversion, when free energy and information within the system begin to concentrate faster than entropy depreciates them (Kompanichenko, 2017, 2019). Such a transition occurs through an enhanced and targeted response of the organic prebiotic system to high-frequency oscillations of physicochemical parameters in a nonequilibrium environment like hydrothermal fluids (Kompanichenko, 2023).

Managadze *et al*. (2009) proposed that the initial emergence of living matter could have occurred in the plasma torch generated during the meteorite's hypervelocity impact onto the planetary surface, where ensuing conditions drove the abiogenic synthesis of complex organic compounds. The plasma torch from meteorite impacts could have played an important role in the formation of homochiral molecules (Managadze, 2007; Managadze *et al*., 2003, 2016) as well as the synthesis of various compounds relevant for the emergence of life (Managadze *et al*., 2010).

A principal contribution to the theory of the origin and evolution of life is the notion put forward by the famous microbiologist G.A. Zavarzin (2015), who pointed to the microbial community as the simplest biological system consisting of microorganisms (units of life) linked to each other trophically. He indicated the microbial community as the main component and the architect of the biosphere (Zavarzin, 2001, 2004a) and believed that life can only emerge as a community, with the prokaryotic microbial community being the priori generator of Earth's biosphere. An individual organism can only survive as part of a community. He named epicontinental soda reservoirs as a possible ecosystem where the first biotopes could have originated (Zavarzin, 1993). Using a systems approach to the study of microbial processes, he believed that the microbial community drives the meaning of its activity and sustainability within the geosphere-biosphere system, being a system of a higher level. He also argued that evolution on Earth was additive, with the new complementing but not rejecting the old (Zavarzin, 2004b) and that cooperation rather than competition plays a key role in evolution (Zavarzin, 1995a).

The importance of the geochemical approach to the origin of life was initially realized by M.Y. Marov. He contended that the conditions for the emergence of life are closely related to geology and geochemistry and pointed to Vernadsky's fundamental ideas about the origin and development of the biosphere and its influence on the Earth's geochemical processes (Marov, 2013). In geology, we can now scientifically address the origin of the biosphere; geochemistry precisely defines the conditions required for life's emergence, and biogeochemistry characterizes the geochemical processes within the biosphere mediated by living organisms (Marov, 2015, 2023). Marov suggested that an important stage of pre-biogenic, and possibly biogenic, synthesis of organic matter could have been made in space. Such organic matter, together with water, could have been delivered to Earth by impactors and dust particles (Marov and Ipatov, 2005). Marov also suggested the important connection between various philosophical concepts and the emergence of astrobiology (Marov, 2015). With the direct participation of Marov, pioneering studies of Venus and Mars were carried out, which received worldwide recognition (Marov, 2024).

It is also necessary to note the works of V.A. Tverdislov on chiral dualism as a systemic factor in the origin and evolution of life on Earth (Tverdislov and Malyshko, 2016), V. Matveev and his sorption theory of the origin of life (Matveev, 2017, 2019), as well as V. Gusev's hypothesis on the origin of microorganisms in water clouds with the eventual precipitation via raindrops (Gusev, 2002),

Bacterial paleontology

Bacterial paleontology as a scientific field was created by the academicians of the Russian Academy of Sciences, A.Yu. Rozanov and G.A. Zavarzin (1998). Its main tasks are the investigation of fossil microorganisms: their morphology and sizes; burial conditions; and products of habitability that are reflected in lithologic and geochemical features of rocks (Rozanov, 2021). Bacterial paleontology deals with fossil materials and is useful in the analysis of the genesis of sedimentary rocks, and sedimentary mineral resources including oil and gas. Microfossils were present in almost all sedimentary and sedimentary-volcanic rocks of the earth's crust, *circa* 3.9 billion years ago. The development of bacterial paleontology has led to corrections in interpreting geobiological events during the Archean–Proterozoic

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periods of evolution of the biosphere on Earth. A micropaleontological study of Earth's oldest terrestrial rocks will deepen our understanding of the conditions on the early Earth and elucidate the history of life's development. In addition, some findings of bacterial paleontology may contribute significantly to astrobiology in relation to the origin of life (Afanasyeva *et al*., 2024; Rozanov, 2002, 2024).

Findings of ancient prokaryotic and eukaryotic microorganisms, their links to early Earth environments, and structures resembling fossilized microorganisms in carbonaceous chondrites (meteorites) have challenged established scientific paradigms and sparked active debates on panspermia and the origin of life on Earth (Hoover *et al*., 2018; Rozanov *et al*., 2016). Having analyzed meteorites (some of them are older than the Earth) and terrestrial rocks using modern bacterial paleontology methods, Rozanov concluded that life could originate in the form of a protogenome during the formation of the Solar System, such that primitive micron and submicron sized organisms have existed from the time of the origin of the Solar System to the present-day Phanerozoic era (Rozanov, 2017, 2024). The critical point here is to distinguish ancient microfossils native to the meteorite from terrestrial contaminants and abiogenic structures.

Space research related to astrobiology

Astrochemistry and astrocatalysis

This section includes scientific concepts that consider prebiotic synthesis of organics in space as a principal precondition for the emergence of life.

In this context, a significant contribution is the hypothesis of astrocatalysis that has been developed by the Russian physicists, Snytnikov and Parmon. The hypothesis posits that the preplanetary circumstellar disk of the early Solar System was the most probable site for the primary abiogenic synthesis of prebiotic organic compounds from simpler molecules, ultimately leading to the emergence of life. Catalytically active nanoparticles in a protoplanetary disk facilitated synthesis of complex molecular compounds followed by the RNA world hypothesis and further biological evolution on Earth. The basis of this postulation is the phenomenon of autocatalytic reactions resulting in rapid formation of increased complex organic compounds. Primary synthesis of autocatalysts depends on external sources of energy, as exemplified by the presence of ubiquitous ultraviolet radiation from the young Sun (Parmon, 2002; Snytnikov, 2007a, 2007b, 2008, 2010; Snytnikov and Parmon, 2004; Snytnikov *et al*., 1996, 2002). The universal premise is that life is a cosmic phenomenon, with its emergence and evolution occurring in space after cosmic inflation, progressing toward organic complexity and, ultimately, humans.

Ionizing radiation interacting with formamide ($HCONH_2$) in the presence of meteoritic material drives the catalytic formation of prebiotic organics (e.g., amino acids), which are then sequestered within the mineral framework of those meteorites (Saladino *et al*., 2015, 2016, 2017).

The importance of cosmic factors, and in particular cosmic rays, on the evolution of life is published in the works of Obridko and Ragulskaya. They considered the dynamics of the early Sun, the migration of giant planets, and the formation of the Earth–Moon system as the main influencing factors on the origin of biosphere and geomagnetic fields (Obridko *et al*., 2020; Ragulskaya and Obridko, 2017). These factors are used to assess the potential for detecting prokaryotic life beyond Earth (Obridko *et al*., 2024; Ragulskaya, 2024).

General and practical issues of astrochemistry are studied in the works of Wiebe D.Z. and Stolyarov A.V. They described the relevance of the emergence of a new field of experimental studies, namely laboratory astrochemistry (Wiebe and Stolyarov, 2021). This is necessary to create a comprehensive atomic and molecular database for the purpose of interpreting molecular emission and absorption lines emanating from meteors (Popov *et al*., 2021) and from exoplanet atmospheres (Kozlov *et al*., 2024; Mitev *et al*., 2022; The EXOMOL project (www.exomol.com)). In laboratory experiments, together with colleagues, they also showed that effects related to distinct features of adsorbed molecule photochemistry may change theoretical abundances of some organic molecules by more than an order of magnitude in protoplanetary disks (Wiebe *et al*., 2019), and that the photo-induced reactions in the solid

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phase astrochemistry of the interstellar medium are crucial for the astrochemical modeling (Murga *et al*., 2020). It has been shown that the photodissociation of adsorbed aromatic hydrocarbon molecules proceeds through alternative channels and with appreciably different efficiencies than does the analog process in the gas phase chemistry (Murga *et al*., 2019).

Wiebe considers cosmic rays as an essential astrochemical factor that is significantly relevant in the thermal and ionization balance of molecular clouds, essentially initiating chemical processes in these objects, and stimulating the formation of organic compounds in the icy mantles of interstellar dust grains (Wiebe, 2024).

Studies on modeling chemical evolution during star formation (Kochina and Wiebe, 2014, 2015) and on the synthesis of complex molecules and the formation of water with its subsequent delivery to ancient Earth (Kirsanova *et al*., 2025; Kochina and Wiebe, 2020) have also been published.

Delivery of water and organic species to Earth by volatile-rich impactors such as meteoroids, asteroids and comets, played a central role in shaping the prebiotic chemistry on the early Earth. Oxygen-rich impactors delivered mainly oxidized species such as OH, H_2O, CO, CO_2, SO_2, FeO and CaO to planets (Berezhnoy and Borovička, 2010; Berezhnoy *et al*., 2003, 2024; Popov *et al*., 2021). Low-speed cometary impacts can deliver CH_3OH, NH_3, and complex organic species produced by disequilibrium processes, while C-rich comets with high dust-to-ice ratios serve as sources of hydrocarbons (Berezhnoy *et al*., 2012).

For astrobiological applications it is necessary to ascertain the chemical compositions of comets. Different aspects of cometary science have been developed in Russia. Cometary dust particles enriched by volatile elements (C, H, and O) were observed by the Vega spacecraft during its mission flyby of Halley's Comet (Mukhin *et al*., 1991). UV spectra of pyrene are sensitive to composition of the ice matrix (Freidzon *et al*., 2014), allowing the use of pyrene as a marker of the chemical composition of cometary ices. The stability of polyaromatic hydrocarbons (PAHs) to UV irradiation was studied by Murga *et al*. (2022).

Gontareva suggested that meteorites can play a central role in the evolution of life. Due to their structure, they tend to adsorb organic compounds and catalyze a variety of organic reactions critical to scenarios of life's origins such as peptides and nucleotides, thus, lending support to the RNA world hypothesis. Model experiments on irradiation of solid samples containing minerals and organic compounds were conducted onboard different Russian space stations (Bion, Cosmos, and Mir) with varying duration, altitude, and radiation conditions (Gontareva *et al*., 2013).

In model experiments on the synthesis of organic matter under the action of pulsed electric discharges simulating lightnings in planetary atmospheres, e.g. on a Jupiter's reducing atmosphere (Kalinichenko *et al*., 1977), it was shown that this process is much more efficient in an oxygen-free atmosphere, which correlates with the hypothesis that Earth's atmosphere was reducing when life emerged. Model experiments, simulating meteorite impact conditions, showed efficient formation of various saturated and unsaturated C1–C6 hydrocarbon molecules even in neutral atmospheric conditions (Gerasimov, 2002; Gerasimov *et al*., 1984).

Subsequent experiments simulated impact vaporization with peridotite and carbonaceous chondrites (Murchison CM2 and Kainsaz CO3) as targets, under helium, hydrogen, and $N_2 + CH_4$ atmospheres, to test the role of meteoritic or atmospheric volatiles in organic synthesis (Zaitsev *et al*. 2016, 2018). Analysis of condensates from experiments with vaporization of peridotite in the nitrogen + methane (N_2 96% + CH_4 4% by volume) atmosphere resulted in detection of approximately 80 complex organic compounds (Figure 7). Simple protein and non-protein amino acids including some hydroxy-, and dicarboxylic acids as well as urea (the main product) were found at ppm levels, which corresponded to the abundances of these molecules observed in carbonaceous chondrites (e.g., in CM2-chondrite Murchison).

Such impact-induced production of organic compounds on the early Earth and on distant planets with reduced or neutral atmospheres must be considered as a valuable input of precursor organic molecules for further biological evolution (Gerasimov *et al*., 1991; Mukhin *et al*., 1989).

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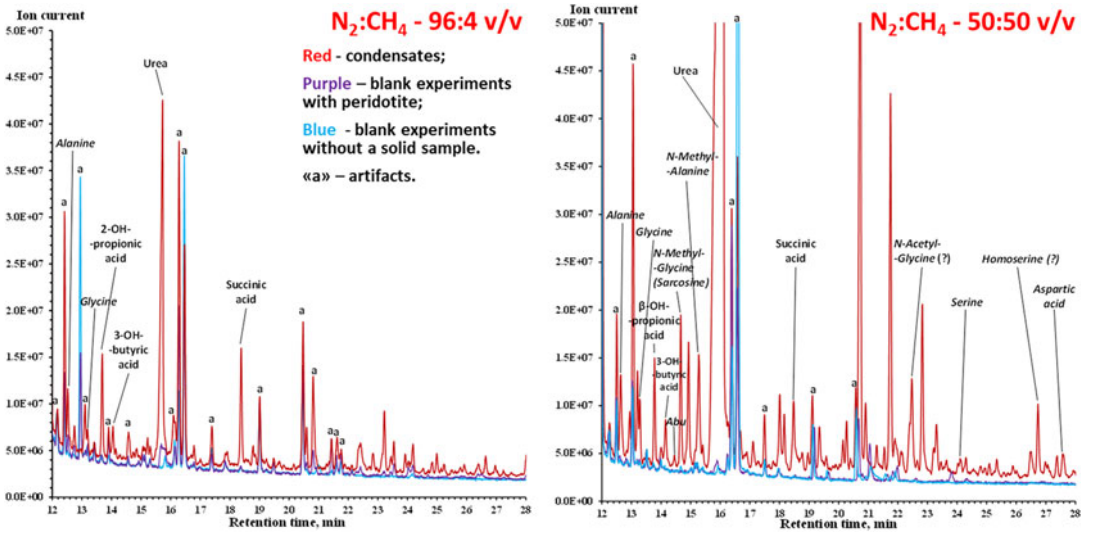


Figure 7. *Total ion current chromatograms of tBDMS derivatives of the ultrasonic water extraction products isolated from 20 mg of the condensates obtained by laser vaporization of peridotite in nitrogen–methane (96:4 and 50:50) atmospheres (Zaitsev* et al*, 2018).*

The similarity between organic matter in pristine meteorites and in their impact-generated condensates under neutral atmospheric conditions suggests that these compounds were likely to have been formed through analogs high-energy impact processes in neutral – possibly vacuum – environments, rather than within a dense, hydrogen-rich protosolar cloud.

The research group from Yekaterinburg has developed an Ice Spectroscopy Experimental Aggregate (ISEAge) for experiments on transmission infrared spectroscopy of the interstellar ice analogs. Using the ISEAge, IR spectra of solid HCN in astrochemically-relevant environments were obtained followed by the interpretation of the open JWST data (Ozhiganov *et al*., 2024). It was shown that solid HCN may constitute up to 1% of the total amount of interstellar ices. This is the first Russian experimental study of the interstellar ice analogs.

The same methodology was applied to estimate, for the first time, the content of gaseous and solid methane towards the protostar IRAS23385+6053 (Nakibov *et al*., 2025). The main finding was that solid methane is mixed with water and CO_2 in the icy mantles of interstellar grains. Furthermore, a tentative detection of nitrous oxide (N_2O) in the ices toward IRAS23385+6053 has been reported.

Additionally, it was found that the highest abundance of gas-phase methanol in the dense cores of the filament L1495 is observed at the regions characterized by the moderate depletion of gas-phase CO (Punanova *et al*., 2022). This finding supports the scenario of CH_3OH formation in chemical reactions on interstellar grains during the active CO freeze-out from the gas phase.

Finally, a comprehensive rate-equations-based chemical model MONACO capable of simulating the time-dependent evolution of chemical composition in star-forming regions accounting for gas-phase and grain-surface chemistry, including non-diffusive surface kinetics (Borshcheva *et al*., 2025). In this work, for the first time, abundances of complex organic molecules (COMs) in the prestellar core L1544 are accurately reproduced, as well as their spatial distribution and observed COMS-to-methanol ratio.

Cosmic dust

Cosmic dust is defined as particles of solid matter ranging in size from fractions of a micron to several microns. Cosmic dust is formed mainly during the disintegration of periodic comets, as well as during the fragmentation of asteroids, and plays a central role in various stages of star formation (Ivlev *et al*.,

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2024). Interstellar dust particles (IDPs) have sizes 0.1 mμ to several nm and are present in the interplanetary medium (Kochina and Wiebe, 2020). Studies of cosmic dust falling onto the Earth's surface are important for reconstructing the geological history of the planet and obtaining data on the paleoclimate, while also advancing solutions to fundamental questions about interplanetary matter and its role in the origin of life (Grachev *et al*., 2008). Cosmic dust is found in deep-sea marine; in oceanic sediments and snow covering mountain peaks, Arctic and Antarctic as well as in the earth's rocks and other natural tablets. Cosmic dust delivers a unique influx of matter and energy to Earth, continuously arriving from space and actively shaping the planet's geochemical and geophysical processes, while also impacting on biological lifeforms, including possibly humans.

Sphagnum moss can also be used as an accumulator of cosmic dust and can be a bio-monitor in its study (Tselmovich, 2020; Tselmovich *et al*., 2019). Cosmic dust in moss samples collected in the USA, Georgia, Belarus and Russia consisted mainly of Fe, Fe-Ni, and Fe-Cr minerals (Frontasyeva *et al*., 2018)

Cosmic dust in Antarctic ice contains the smallest amount of terrestrial dust impurities and does not contain man-made particles. In the snow cover of Central East Antarctica, Vostok station, stony-iron micrometeorites were first to be found (Bulat *et al*., 2018a, 2018b). In the summer season the first detection of tin and copper particles in the magnetic component of space matter from Antarctica collected by a magnetic trap was reported (Tselmovich *et al*., 2025).

Russian scientists have developed a method for identifying interstellar comets using ground-based instruments, which involved studying cosmic dust settling on Earth. It is based on the results of European colleagues in identifying the Ni and Fe metal spectral lines previously detected in the spectra of interstellar comets (Guzik and Drahus, 2021). Cosmic dust particles differ depending on where they were formed. For example, those of asteroidal origin are hard and dense, while particles of cometary origin have a looser and more porous in structure. The presence of nickel films in terrestrial dust particles, in particular, indicates their cometary origin (Tselmovich *et al*., 2023).

Biomarkers in the atmospheres of terrestrial exoplanets

As part of the scientific difficulties of searching for habitable worlds, Russian scientists are conducting theoretical studies that propose certain criteria for the potential habitability of planets. In addition to key habitability parameters, such as the presence of water and suitable physicochemical conditions, an important factor may be the presence of an N_2–O_2 dominant atmosphere on the planet. This gas can form on the extraterrestrial planet as a result of both geological and biological processes (Lammer *et al*., 2019). Hence, N_2O, NO_2, NO, and the N_2–O_2 dimer can serve as direct indicators – and thus biomarkers – of such an atmosphere, with their spectral signatures potentially detectable in the UV and IR bands of Earth-like exoplanet's upper atmospheres (Schwieterman *et al*., 2022; Sproß *et al*., 2021; Tsurikov *et al*., 2024b).

The task of analyzing such biomarkers in the atmosphere of identified exoplanets is included in the scientific program of the 2-meter class Spektr-UV space telescope (ST) being developed in Russia (launch scheduled for 2029) (Sachkov and Kopylov, 2024), which will continuously obtain data in the UV range. To assess the possibility of detecting NO molecule as a biomarker, the studied models of NO formation (Shematovich *et al*., 2023, 2024), radiative transfer (Tsurikov and Bisikalo, 2023) and the Spektr-UV ST exposure calculator (Tsurikov *et al*., 2024a) were used. In addition, transmission spectroscopy relies on measuring the change in stellar flux when a planet transits its host star compared to the out-of-transit baseline. According to calculations by Tsurikov *et al*. (2024b), under Earth-like atmospheric conditions, detecting NO with the Spektr-UV observatory's LSS spectrograph ($R = 1000$) is feasible only for exoplanets located relatively close to Earth. The maximum distances from the Earth to exoplanets in this case should not exceed 2 pc for reliable signal detection (significance level 3σ) for a reasonable observation time (<200 hours). However, intense electron precipitation into the atmospheres of exoplanets near stars with high stellar wind flows can lead to a significant increase in the NO concentration and an increase in the maximum distances to exoplanets

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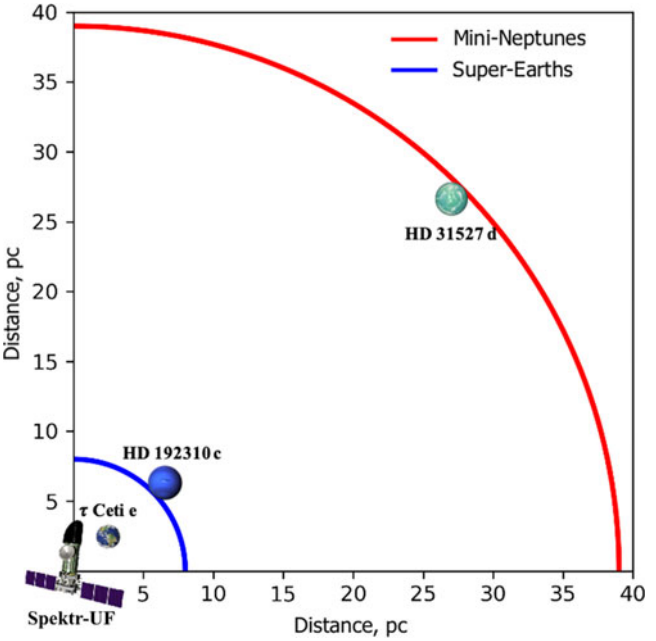


Figure 8. *Limiting distances to typical super-Earths (blue curve) and mini-Neptunes (red curve) for detection of the nitric oxide (NO) biomarker molecule in their atmospheres with ST Spektr-UV with a significance level of 3σ and a total observation time of less than 200 hours. Colored spheres indicate candidate exoplanets earmarked for nitric oxide search with ST Spektr-UV.*

for signal detection in the NO γ-bands to 8 and 40 pc for typical super-Earths and mini-Neptunes (Shematovich *et al.*, 2024). Among the 35 nearest (<100 pc) terrestrial exoplanets located in the habitable zone (HZ), suitable candidates for NO detection with ST Spektr-UV are (Figure 8): super-Earth τ Ceti e; mini-Neptunes HD 192310 c and HD 31527 d.

The other exoplanets in the habitable zone include HD 109365 b, HD 69830 b and HD 10180 g that are possible contenders for the presence of NO. All of these exoplanets are candidates for the upcoming ST Spektr-UV science program to search for biomarkers.

Programs for exploring the cosmic bodies of the Solar System

Russia prioritizes the organization of various space programs and missions – both near-Earth and for exploring the planets of the Solar System – within which astrobiology research is planned. Currently, active developments are conducted in relation to the exploration of Mars and Venus, where one of the tasks is to search for life or traces of its existence in the distant past on these planets.

Mars

Mars is the planet in which astrobiologists show the greatest interest, since it is theorized to have "ecosystems," mainly at the subsurface level, where the conditions are largely similar to those in the cold Arctic and Antarctic zones on Earth.

During the Mars space exploration program, the main data was initially collected by orbiting unmanned spacecraft. Simultaneously, the probe "Mars-3" first successfully landed on the surface of the planet in 1971, and "Mars-6" first transmitted collected data pertaining to the Martian atmosphere.

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Since the early 2000s, Russian scientists have led or participated in several space astrobiological experiments of importance, carried out on board NASA, ESA, or joint ESA-Roscosmos missions. The High-Energy Neutron Detector (HEND) on NASA's orbiter, Mars Odyssey, first mapped hydrogen-bearing areas on the surface of Mars to determine the mass fraction of water ice and chemically bound water to a depth of 1–2 m by measuring the flux of secondary neutrons emitted from the surface due to the action of cosmic rays (Mitrofanov *et al*., 2004). These investigations have been extended to *in situ* surface measurements by the Dynamic Albedo of Neutrons (DAN) experiment aboard NASA's Curiosity rover. In contrast, the FREND neutron telescope aboard the ESA–Roscosmos Trace Gas Orbiter (TGO) mapped surface hydrogen with roughly tenfold higher spatial resolution than HEND (Malakhov *et al*., 2022).

The radiation environment on Mars is too harsh for life to be sustained and, naturally, affects all potential life forms (see, e.g., Pavlov *et al*., 2010). High-energy radiation and the associated risks to human health largely determine the planning of future human missions to Mars. One channel of FREND, the radiation monitor Liulin-MO, monitors galactic cosmic rays and energetic solar wind particles in the orbit of TGO (Semkova *et al*., 2024). HEND and DAN data have also been used to assess the radiation environment at the surface of Mars (Litvak *et al*., 2020; Martinez Sierra *et al*., 2023). The Martian atmosphere's current ability to shield the surface from sterilizing solar UV radiation is demonstrated by SPICAM's UV spectrometer measurements aboard ESA's Mars Express mission (Lefèvre *et al*., 2021; Müller *et al*., 2001).

Possible present-day life on Mars could manifest itself in its atmospheric composition. Methane, a primarily biogenic gas on Earth, has long been considered a possible signature of life (e.g., Krasnopolsky *et al*., 2004). Methane detections by ground-based telescopes (and spacecrafts) onboard Curiosity rover (Mumma *et al*., 2009; Webster *et al*., 2018) equipped with the Russian experiment, Atmospheric Chemistry Suite (ACS)/the ESA-Roscosmos ExoMars Trace Gas Orbiter (TGO) mission, failed to detect any traces of the gas. The search for methane has been remotely continuing since 2018 by the TGO (Korablev et al., 2019; Montmessin et al., 2021). The TGO upper limits are 10–100 times lower than the most reliable SAM-TLS measurements carried out by Curiosity measurements (e.g., Webster *et al*., 2021), highlighting the inconsistency with current understanding of both Martian atmospheric chemistry and physics. The highly debated issue of Martian methane remains the focus of the scientific community and TGO continues its hunt for methane.

The Russian ACS/TGO, as well as the SPICAM and PFS/Mars Express experiments with Russian participation, have collected a copious number of datasets on the Martian atmosphere and its losses over time, summarized in recent reviews (Määttänen *et al*., 2024; Montmessin *et al*., 2024; Vandaele *et al*., 2024). Together with the global mapping of the surface composition provided by the joint French-Russian OMEGA/Mars Express experiment (e.g., Bibring *et al*., 2006), these results collectively shed light on past conditions on Mars, with major astrobiological implications.

The astrobiology part of the Phobos-Grunt mission (Phobos LIFE experiment), which included the exposure of biological samples in a simulated meteoroid during the flight to Phobos being an experimental test for the panspermia hypothesis (Betts *et al*., 2019; Kotsyurbenko *et al*., 2012), but the mission failed. Further, astrobiology research on Mars was carried out mainly in the laboratory during various experiments that simulated Martian conditions and studied the survival potential of terrestrial organisms.

Venus

Over the past few years, interest in the astrobiology of Venus has grown rapidly due to both proactive and active consideration for the existence of living entities in the dense cloud layers; within such layers a fairly high concentration of some "absorber" of ultraviolet radiation of unknown nature was recorded (Perez-Hoyos, 2018). A number of astrobiologists believe that biological macromolecules could act as an absorber and, consequently, a microbial community is highly likely to be present in certain pockets of

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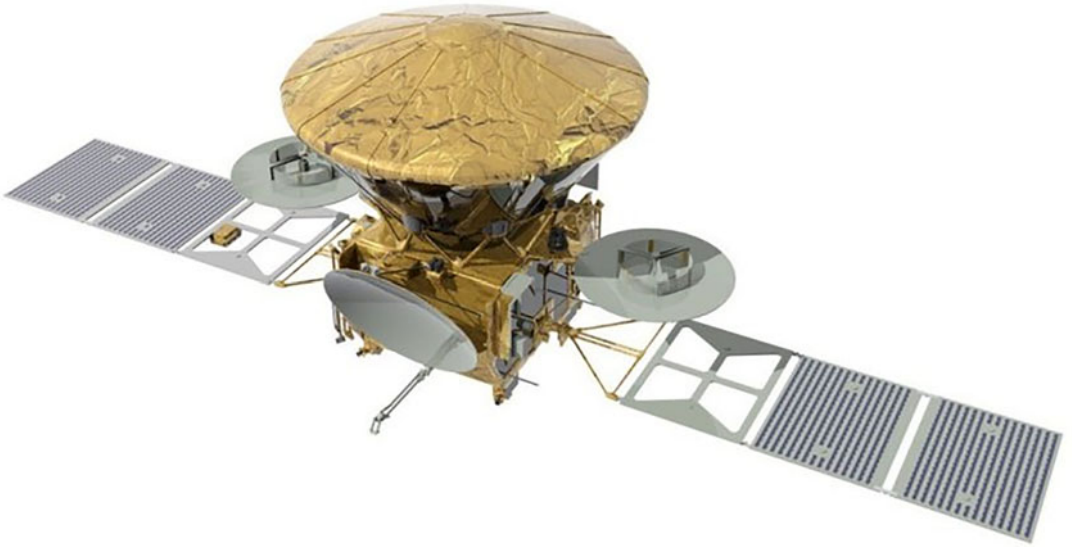


Figure 9. *Venera-D space station. Graphics by NPO "Lavochkin."*

clouds of Venus, driving biogeochemical cycles that support them (Grinspoon, 1997; Limaye *et al*., 2018). It is proposed that, in such layers, hypothetical microbial communities could exist in aerosols being a concentrated aqueous solution of sulfuric acid, for instance. Microorganisms in such a specific "air" habitat are to be exposed to several extreme factors simultaneously, the main ones being very low values of pH and water activity. The principal strategies for survival under these conditions should be the availability of effective biochemical mechanisms which are resistant to the impact of adverse environmental factors and use all possible methods of extracting energy in such an ecosystem to maintain the sufficient biomass of microbes in order for the entities to reproduce (Kotsyurbenko *et al*., 2021; Skladnev *et al*., 2023). Venus has always been one of the priorities of the space research program in Russia. The history of successful investigations of Venus during the Soviet Union era is primarily associated with the sending of a whole series of spacecrafts to Venus, culminating in 10 successful landings on its surface: Venera and Vega in 1970–1985 (Kotsyurbenko, 2023; Sagdeev *et al*., 1986a).

The SPICAV-SOIR experiment has been carried out on board ESA's Venus Express project with a significant Russian contribution. Results of astrobiological relevance include atmospheric chemistry (Belyaev *et al*., 2012; Evdokimova *et al*., 2021), properties of the cloud layer (Luginin *et al*., 2024), and refinement of measurements of the deuterium-to-hydrogen ratio (Fedorova *et al*., 2008) related to past conditions on the planet. Currently, several world-wide space missions to Venus are being planned (Widemann *et al*., 2023) and, in some of them, experiments are included to search for biomarkers in cloud layers (Kotsyurbenko *et al*., 2024).

Russia is working on organizing another Venera-D mission, which aims to study Venus both from the orbit and *in situ*, using an orbiter (Figure 9), a lander and two airborne balloons.

Each part of the spacecraft will be able to contribute to the astrobiological endeavors using various scientific payloads. The composition and distribution of the unknown UV absorber in the atmosphere of Venus can be studied in detail during the Orbiter's onboard UV and IR spectrometers from a high elliptical, polar, orbit. During the Lander's short descent through the cloud layer its instruments will measure the composition and the microphysics of the cloud aerosol, including isotopic ratios – these results will provide new information on the chemical cycles and cloud properties, confirming or negating the presence of any possible ecosystem. Two balloons will be deployed to the altitude range of 53–57 km for at least 20 days (Kotsyurbenko *et al*., 2024) in order to perform a long-term analysis of the middle cloud layer properties, where temperature and pressure are close to Earth surface average.

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The astrobiological applications of Venera-D measurements were greatly inspired by two workshops organized by the IKI/Roscosmos/NASA Venera-D Joint Science Definition Team (JSDT) in 2019 and 2021 (see references to Venera-D workshops). The JSDT also supported two special issues of the Astrobiology journal, also related to the aforementioned workshops (see references to Venus (2021) and Venus-2 (2024)).

Other cosmic bodies

It is worth noting that, within the framework the Vega program, in addition to Venus, Halley's comet was also studied and the chemical composition of its coma was determined, which included a mixture of carbon-hydrogen-oxygen-nitrogen (CHON) complex compounds (Kissel *et al*., 1986).

Astrobiological studies of the satellites of the giant planets have, to date, remained largely theoretical. Titan has inspired proposals for biogeochemical cycles and potential biomarkers, grounded in its unique organic-rich environment (Simakov, 2000, 2004).

At the present time, the promising Russian space project is lunar exploration by the orbiter (Luna-26) and landers (Luna-27a and b) followed by the lunar station Luna-28 that is designed to deliver samples of lunar polar regoliths back to Earth. It is known that the regolith in the vicinity of the lunar poles may contain several percentages by weight of water ice and other cometary compounds, preserved in pristine form in polar permafrost. Studying samples returned to Earth by the Luna-28 return capsule will enable experimental tests of the panspermia hypothesis (Mitrofanov, 2024).

The prospective goal of the lunar program, includes among national missions, the creation of the International Lunar Research Station (ILRS) in cooperation with China and other countries that will require efforts of astrobiologists for conducting different biological experiments on survival of terrestrial organisms pertaining to lower gravity and higher radiation (see also the section below).

Orbital biological experiments

In September 1968, Zond 5 became the first circumlunar mission to carry living organisms and return safely to Earth. On board the spacecraft was a diverse biological payload, including animals (tortoises, fruit flies, and mealworms); plants such as Chlorella, spiderwort, onions, and seeds of higher plants; as well as microorganisms (E. coli) and cultures of human cells (Parfenov and Lukin, 1973).

First experiments on the possibility of prebiotic synthesis of organic molecules in open space have been conducted during space missions on the Soviet orbital stations Salyut-6 (1977–1982) and Salyut-7 (1982–1991). The formation of such nucleosides as adenosine, deoxyadenosine, thymidine, as well as nucleoside-like molecules have been confirmed (Kuzicheva and Gontareva, 2003).

Scientific research in near-Earth orbit occupies an important place in the Russian space program. Biological experiments are regularly conducted on the International Space Station (ISS). Moreover, during the 27 years of the station's operation, the majority of all research (more than 40%) has been devoted to space biology and physiology (Orlov *et al*., 2023). In the framework of biological experiments (not considering those of medical nature, which make up a significant part of all experiments), the influence of microgravity on the vestibular apparatus of snails was studied ("Statoconia," 2005–2008); regeneration of snail's eye and body fragments of planarians ("Regeneration", 2014–2019); activation of African mosquito larvae ("Aquarium," 2014); alteration in the genetic apparatus of plants ("Plants," 1999–2022); as well as the influence of cosmic radiation on the genetic apparatus of fruit flies ("Poligen", 2010) and other experiments – see Table. 3.

In "Biorisk" and "Test" experiments on the exterior of the ISS a number of strains of bacteria, archaea and fungi were "seeded" in different types of soil, plant seeds, dormant forms of insects, lower crustaceans, and vertebrates were exposed to the duration 13 months to two years. It was found, that most organisms remained viable (Deshevaya *et al*., 2024; Novikova *et al*., 2011). These experiments

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Table 3. *Some orbital space experiments of astrobiological importance*

Spacecraft/"Program"/ *Experiments*	Program tasks
ISS	
"Bacteriophage"	-Study of biological and genetic properties of bacteriophages.
"Bioecology"	-Study of physiological and biochemical properties of microorganisms
"Biofilm"	that degrade oil pollution and produce plant protection products.
"Biorisk" and "Test"	-Study of the features of formation of bacterial films on carriers.
"Electronic nose"	-Study of the effect of radiation outside the station on plant seeds,
"Microbiological monitoring"	dormant eggs of lower crustaceans, mosquito larvae, strains of microorganisms in different types of soil.
"Plasmid"	-Study of microbial contamination of materials on the ISS using the portable gas sensor system E-NOS in order to ensure biosafety of the space-station habitat. -Study of the formation and spread of microorganisms in the living compartments of the ISS. -Study of the frequency of transfer and mobilization of plasmids in bacteria and the formation of polyresistance.
Bion-M1	
"Biokont-B"	*-Study of the influence of space flight factors on the vital activity and*
"Bioimpedance"	*functional characteristics of microorganisms.*
"Microcosm"	*-Obtaining scientific data on the morphofunctional state of cell cultures*
Recombination	*in space flight conditions by monitoring the bioimpedance characteristics*
Lysogenization	*of a cell culture sample.*
Metabolism	*-Analysis of the influence of space flight factors on the biological activity*
Bioelectricity	*of microorganisms exposed in a thermostatted container inside an*
"Abiogenesis"	*unmanned spacecraft for 30 days of space flight.* *-Study of the influence of FCP on the exchange of chromosomal DNA during crossing of strains of the genus Streptomyces.* *-Influence on the level of exit from the cell (spontaneous induction) of the phage fC31 in lysogenic strains of Streptomyces.* *-Influence on the biosynthesis of the antibiotic tylosin in Streptomyces fradiae.* *-Influence on the vital activity of the electrogenic bacterium Shewanella oneidensis MR-1.* *-Identification of possible pathways and mechanisms of chemical evolution in the absence of water on the surface of space bodies exposed to the directed effects of cosmic radiation and temperature changes.*
Foton-M 4	
"Biocultivator"	-Study of the process of biodegradation of polyethylene film by
"Biokont-FE"	microorganisms without adding additional ingredients and forced removal
"Meteorite"	of metabolic products under space flight conditions.
"Exobiofrost"	-Study of the influence of space flight factors on the vital activity and productive capacity of economically valuable microorganisms in the absence of a magnetic field, as well as to study the influence of space flight factors on the development of reptile embryos. -Study of the survival of thermophilic microorganisms in the mass of a mineral when it passes through dense layers of the atmosphere. -Study of the stability of the permafrost microbial consortium under space exposure conditions.

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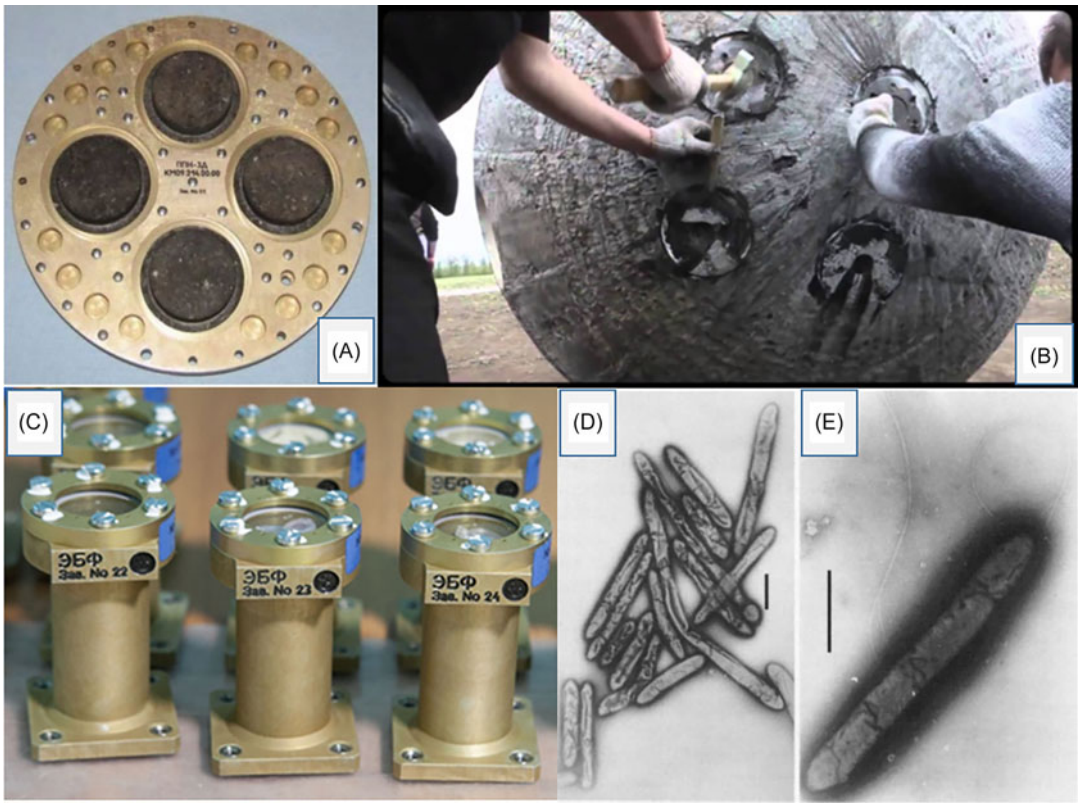


Figure 10. *(***A***). The "Meteorite" product: size 17X70, 24 holes with a diameter of 1.5 mm and a depth of up to 8 mm are drilled in the frontal plane. Four similar products are placed in a container with a lid to prevent overheating during the return of the satellite. (***B***). Removal of the "Meteorite" products after the return of the satellite. (***C***). The "Exobiofrost" product. (***D***) and (***E***). Electron micrographs of* Thermoanaerobacter siderophylicus *strain SR4^T cells grown in basal medium with peptone as an electron donor and sulfite as an electron acceptor – the former (***D***) negatively stained whole-cell specimen and the latter (***E***) cell with peritrichous flagella (negative staining). Bars, 1 μm. Modified from (Slobodkin* et al.*, 1999).*

provided evidence that not only bacterial and fungal spores but also dormant forms of higher organisms have the capability to survive a long-term exposure in outer space.

Of great importance for astrobiology are the results of the Russian programs "Bion" and "Photon" (Table 3), biosatellites launched into low near-Earth orbits. Experiments have been conducted from 1973 to the present-day to study the effect of ionizing cosmic radiation and prolonged microgravity on the cellular, tissue and systemic levels of organization of animals, plants, and microorganisms (Aniskina *et al*., 2023; Levinskikh *et al*., 2000). The biological objects on board were monkeys, rats, mice, fruit flies, geckos, turtles, fish, lower and higher plants, yeast and bacteria.

At present, astrobiological experiments are planned and conducted on the Bion-M and Foton-M series spacecraft. The most significant of these are the Meteorite, Microcosm, Abiogenesis and Exobiofrost experiments.

The goal of the Meteorite experiment is to study the survival of microorganisms embedded in mineral rock as it passes through dense layers of the Earth's atmosphere. Biomaterial in the form of various thermophilic bacteria was placed in holes drilled in a piece of basalt disk (Figure 10a). After such an artificial meteorite passed through the dense layers of the Earth's atmosphere with the satellite

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(Figure 10b), of the 9 tested species of microorganisms (*Moorella thermoacetica, Clostridium thermosaccharolyticum, Clostridium difficile, Thermoanaerobacter siderophylus, Desulfotomaculum nigrificans, Clostridium thermosulfurogenes, Clostridium thermocellum, Bacillus pumilus and Aspergillus niger*), only two were able to survive: *Thermoanaerobacter siderophylus*, isolated from the hot iron-containing spring of Karymsky volcano in Kamchatka, and *Bacillis pumulus*, isolated from the outer surface of the International Space Station (Slobodkin *et al*., 2015).

The results of the experiments proved that terrestrial organisms can survive a meteorite impact while being enclosed in the satellite. Obviously, the thicker the matrix in which the microorganisms are located, the greater their chances of surviving a meteorite impact. Thus, the possibility of lithopanspermia in experiments with terrestrial extremophiles was demonstrated for the first time (Slobodkin *et al*., 2015).

In the Microcosm series experiment, various microorganisms were exposed in a thermostatted container located inside the Bion-M 1 spacecraft during a 30-day space flight. Several separate experiments were conducted within the Microcosm series, as presented in Table 3.

In the Exobiofrost experiment, the stability of the permafrost microbial consortium was investigated in special containers under conditions of exposure in outer space (Figure 9c).

A significant part of the bacterial community retained viability after a month of flight, and the number of cultured bacteria decreased by no more than an order of magnitude (Figure 9d) (Rivkina *et al*., 2019).

In the "Abiogenesis" experiment, researchers investigated potential pathways and mechanisms of chemical evolution on water-deprived cosmic-body surfaces exposed to targeted cosmic radiation and temperature variations. Experimental samples were dry films of the amino acids glycine and phenylalanine, as well as of the nucleoside uridine with the addition of inorganic phosphate Na_2HPO_4 and various minerals of terrestrial and extraterrestrial (meteorite) origin after application and subsequent drying of their solution on round substrates made of monolithic polycarbonate. As a result of the experiment, dimers and trimers of glycine, as well as trace amounts of longer polymers, were formed, and especially intensively in the sample with meteorite matter, which indicates the possibility of organic synthesis reactions in space conditions.

Additionally, several Russian research groups are conducting laboratory experiments on plants to understand how they react to cosmic environmental stressors (ionizing radiation, weak or fluctuating magnetic fields, microgravity) and identify the mechanisms that trigger acclimatory or protective responses that may be critical for designing future space missions.

It has been shown that enhanced ionizing radiation in doses comparable to "space" levels; hypomagnetic conditions; and ultra-low-frequency magnetic fields alter morphometric traits and physiological activity in higher plants (*Arabidopsis thaliana*, *Triticum aestivum*, and *Nicotiana tabacum*) (Grinberg *et al*., 2021, 2023, 2025). Exposure to ionizing radiation and modified magnetic fields markedly alters and often amplifies stress signals and regulatory pathways triggered by other adverse factors, thereby shaping the overall physiological status of plants under combined environmental stress (Grinberg and Vodeneev, 2025; Gudkov *et al*., 2019; Pirogova *et al*., 2024).

The absence of a gravity vector influences the growth and development of *A. thaliana* as realized by increased transcriptomic and proteomic analyses (Frolov *et al*., 2018). The important role of phytohormone redistribution and cytoskeletal remodeling in plant responses to the lack of a stable gravity vector has been demonstrated (Pozhvanov *et al*., 2021).

Recent studies, including Saburov *et al*. (2024), show that *Arabidopsis thaliana* lines chronically exposed to radiation in the Chernobyl exclusion zone develop enhanced tolerance to ionizing radiation, and when combined with simulated microgravity experiments, they provide key insights into how plants adapt to extreme space-like environments.

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Extreme Earth ecosystems

One of the important areas of astrobiological research in Russia is the study of Earth's ecosystems, which serves as analogs of potentially inhabited extraterrestrial systems (Figure 4). In these habitats, key studies focus on diversity, metabolic properties and adaptive survival mechanisms of microorganisms under harsh environmental conditions. Such habitats can also be explored to search for and isolate new extremophilic organisms with unique characteristics.

In this area, it is necessary to note the series of studies by A.A. Imshenetsky, who dealt with issues of survival of microorganisms under extreme conditions both in artificial and natural environments. Notably, he discovered that rocks and meteorites can draw microorganisms into the interior through microcracks, then help preserve their viability (Imshenetsky *et al.*, 1966); the inference being that these microorganisms can survive in the high vacuum of space (Imshenetsky and Lysenko, 1965) located at altitudes of 77 km (Imshenetsky *et al.*, 1978). An important contribution in this area was the work of Lizina-Lazovsky's group which studied the survival of microorganisms in "Photostat-I," the first chamber created in Russia which simulated Mars conditions, (Zaar *et al.*, 1970).

Currently, laboratory experiments have been conducted to simulate the extreme conditions characteristic of various cosmic bodies. Under Martian-like shallow subsurface conditions – at low pressures of 0.01–0.1 mbar – mesophilic terrestrial bacteria (Vibrio sp.) were shown to metabolize and reproduce in regolith analogs (Pavlov *et al.*, 2010). Cheptsov *et al.* (2019) demonstrated that temperate soil microorganisms remain viable after exposure to 148 kGy of gamma irradiation. Notably, *Deinococcus radiodurans* embedded into a simulated Europa-analog ice at −130°C and pressure of 0.01 mbar could survive with the dosage of 50 kGy irradiation (Pavlov *et al.*, 2019). Cheptsov *et al.* (2021a) demonstrated that bacterial radio-resistance depends markedly on the mineral matrix supporting the cells and that survival rates rise as radiation intensity decreases, even when metabolic activity is absent.

Within "TARDISS" project organized by the Joint Institute for Nuclear Research (JINR), researchers are actively investigating radiation-resistant organisms (bacteria, fungi, and tardigrades), the molecular mechanisms of extreme radio-resistance, and their applications in medicine, space research, biotechnology as well as astrobiology. Among the most recent findings are studies of unique tardigrade intrinsically disordered proteins – particularly the DNA-protective properties of the Dsup protein, its structural features, and the development of extremophile-inspired protectors for other animals and humans (Zarubin *et al.*, 2023, 2024). Also, the metagenomic studies are investigated by this JINR scientific group within extreme ecosystems, such as the vicinity of a nuclear reactor and in the Baksan Neutrino Observatory (INR RAS), one of the deepest underground laboratories (>2 km) in Russia and North Caucasus (Tarasov *et al.*, 2024; Zarubin *et al.*, 2021b). Furthermore, within this unique underground facility, the transcriptomic-based studies are performed to investigate the biological impact of secondary cosmic radiation, high-energy muons and reduced natural background radiation are performed (Zarubin *et al.*, 2021a, 2025).

Next, under simulated Martian conditions a decrease in activity of dehydrogenase enzyme by a factor of 1000 from the initial level could occur within 5.7 Myr. Conversely, catalase could remain active for even longer periods (Cheptsov *et al.*, 2021b), indicating the possibility of detecting enzymatic activity by landers in the course of planned space missions.

Metabolism peculiarities of living organisms such as photosynthetic systems and biogenic synthesis of nanoparticles can be considered as the important biomarkers in their detection (Konyukhov *et al.*, 2023; Skladnev *et al.*, 2020).

Deep subsurface ecosystems (500–5000 meters) are also important analogs of various extraterrestrial potentially habitable systems (Onstott *et al* 2019). In Russia, metagenomic and cultivation studies of unique deep subsurface ecosystems associated with oil and mineral water deposits were conducted with the samples taken from the depths of approximately 1 to 3 km (Frank *et al.*, 2016; Karnachuk *et al.*, 2019; Zavarzina *et al.*, 2025). Recently, the first modern analog of the presumed habitat of the Last Universal Common Ancestor (LUCA) of all the living organisms was identified and described at the deep subsurface water-bearing horizon of the Yessentukskoye Mineral Water Basin. This 1 km-deep

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ecotope is characterized by high partial pressure of CO_2; high magmatic activity; and reduced environment that favors stable predominant of a hydrogenotrophic acetogenic autotrophic bacterium among the microbial community. Evolutionary reconstructions predict LUCA, which lived from 4.30 to 4.00 billion years ago and played a key role as the primary producers of organic matter in the early stages of the Earth's biosphere history. LUCA had a nearly robust and complete metabolic inventory (Zavarzina *et al*., 2025).

The discovery of microorganisms that can survive and thrive in extreme environments, which may also be typical for some extraterrestrial systems, has contributed to the active development of astrobiology (Nascimento-Dias and Martinez-Frias, 2023).

Currently, in the absence of data on extraterrestrial organisms, the primary focus of microbiologists involved in astrobiology is the study of diverse extreme terrestrial habitats which are then considered as hypothetical extraterrestrial environments.

Cold ecosystems

The putative extraterrestrial environments where life could potentially exist are in fact cold places. The main, well-studied, cosmic body where such conditions do exist is Mars; here the existence of subsurface life is a realistic possibility (Beaty *et al*., 2005; Gilichinsky, 1997; Gilichinsky *et al*., 1992, 1993, 2007; Vorobyova *et al*., 1997), because life would be protected from sudden temperature changes on the surface and from the ionizing radiation, which would otherwise be incinerated much earlier in the geological time-frame (Pavlov *et al*., 2002).

Such systems also include the predicted deep subglacial environments such as the moons Jupiter and Saturn, namely Europa and Enceladus respectively, the comparable best analogs on the Earth are the subglacial Antarctic lakes, especially Lake Vostok.

Frozen soils

The frozen soils of Russia, including the permafrost of the Arctic region, are the best analogs of the hypothetical habitable ecosystem of Mars. Permafrost is a unique subsurface ecosystem in which constant physical, chemical and temperature conditions are maintained for a long duration, from several thousand to several million years, allowing viable microorganisms to survive and flourish.

The first reports regarding viable microorganisms in permafrost appeared in the early 20th century and were reported by Russian scientists exploring the Siberian mammoth localities and Far East subsoils (Isachenko, 1912; Omelyansky, 1911). In later years, a number of independent discoveries of viable microorganisms were made in Trans-Baikal, Northern Ural, Siberia, Canada, and Alaska (Gilichinsky *et al*., 1995; Gilichinsky and Wagener, 1995). In the middle and late 1980's new methods of sampling permafrost – including drilling without fluid – as well as sterility controls, allowed the latest tests to be deployed. In the process it was shown that permafrost is inhabited by swathe of living microorganisms (Gilichinsky, 2002; Gilichinsky *et al*., 1989; Zvyagintsev *et al*., 1985). Importantly, viable microorganisms were found in ancient, estimated to be millions of years old. The age of these microorganisms was inferred from the age of permafrost deposits (Abramov *et al*., 2021; Gilichinsky *et al*., 2007; Soina *et al*., 1995; Vorobyova *et al*., 1997), leading to a reassessment of the limits of the terrestrial biosphere.

These and later studies based on analysis of thousands of samples have shown, that Arctic and Antarctic permafrost are inhabited with a wide diversity of bacteria, archaea, yeasts, filamentous fungi, microalgae, protists, multicellular eukaryotes and viruses, including previously unknown ones (Dmitriev *et al*., 1997; Gilichinsky *et al*., 2007; Kochkina *et al*., 2001; Malavin *et al*., 2020; Shatilovich *et al*., 2018; Shcherbakova *et al*., 2009, 2011, 2016; Vishnivetskaya *et al*., 2006; Vorobyova *et al*., 1997). Notably, it was not just a matter of a few microbial cells, rather that microbial abundance in permafrost was only an order of magnitude lower than in temperate soils. Representatives of different

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physiological and functional microbial groups were found, including heterotrophs and photo- and chemotrophs, aerobes and anaerobes, methanogens, sulfate reducers, iron reducers, nitrifiers, denitrifiers, nitrogen fixers, etc. (Rivkina *et al*., 1998, 2007; Shcherbakova *et al*., 2011; Vorobyova *et al*., 1997). Moreover, it was shown that a lot of permafrost microorganisms are able to grow under subzero temperatures, and metabolic activity *in situ* was shown to survive at temperatures as low as −20°C (Rivkina *et al*., 2000, 2004; Vorobyova *et al*., 1997).

A lot of effort was made to understand how, and in which state, microorganisms survive during the harsh permafrost conditions. It was revealed that a large number of prokaryotes are preserved in a viable but non-culturable state (deep resting state), but they can be readily revived to proliferate again. It was suggested that transition to resting or dormant state is one of the most important adaptation survival strategies (Soina and Vorobyova, 1996; Soina *et al*., 2004; Vorobyova *et al*., 1997). The distinctive ultrastructural characteristics of these cells and the mechanisms governing their transition into and out of dormancy were systematically examined, leading to the identification of several metabolites responsible for these processes (Demkina *et al*., 2000, 2015; El-Registan *et al*., 2005; Mulyukin *et al*., 2009, 2014; Soina and Vorobyova, 1996; Soina *et al*., 1995, 2004; Vorobyova *et al*., 1996). It was evidenced that microorganisms in complex heterogeneous natural medium can be more stress tolerant than in pure cultures, due to the presence of metabolites and enzymes immobilized on mineral matrix. Moreover, it was revealed that dormant cells differ in elemental composition compared to active ones and this has led to development of some approaches for living cells detection in terrestrial and extraterrestrial permafrost, using elemental composition analyses (Managadze *et al*., 2017; Mulyukin *et al*., 2002).

Microorganisms isolated from permafrost were studied for tolerance to a number of extreme parameters, including astrobiology relevant ones. It was found that Arctic and Antarctic permafrost microorganisms in general are tolerant to low and high temperatures, freezing-thawing, freezing-drying, salinity, low and high pH, strong oxidizers, antibiotics, heavy metals and thus they have increased adaptability compared to non-permafrost ones (Belov *et al*., 2020a; 2020b; Gilichinsky *et al*., 2008; Kryazhevskikh *et al*., 2013; Vishnivetskaya *et al*., 2003; Vorobyova *et al*., 1997). In particular, methanogens isolated from permafrost have been shown to be among the most promising models for possible life on Mars. This is because methanogens can withstand effects of perchlorates in concentrations that are found in the regolith of the Red Planet (Shcherbakova *et al*., 2015). The first hypobarophilic bacteria capable of growth under simulated Martian atmospheric conditions were isolated from Siberian permafrost by Nicholson *et al*. (2013), prompting extensive research into these organisms.

An important feature of ongoing studies in Russia is the use, in astrobiological model experiments, not only of pure microbial cultures isolated from different extreme environments, but natural microbial communities as a whole. Such an approach is rarely realized globally (Cheptsov, 2024; Finster *et al*., 2008). In the course of such studies, it was shown that Antarctic permafrost microbial communities are almost not inhibited by the effect of 5% sodium perchlorate, retaining taxonomic and functional diversity, whereas a lot of prokaryotes in pure cultures are unable to survive under such conditions (Cheptsov *et al*., 2021a). Investigations of Arctic permafrost microorganisms *in situ* revealed extraordinary radio-resistance, with some cells surviving gamma-ray irradiation doses of up to 250 kGy (Vorobyova *et al*., 2018). It was found that Arctic and Antarctic microorganisms within the natural community are able to survive simultaneous effects of low pressure, low temperature and ionizing radiation (Cheptsov *et al*., 2017, 2018a, 2018b, 2018c, 2021b), making them polyextremophiles.

Apart from polar permafrost studies, research of such specific environments around volcanic permafrost are underway in Russia. Aerobic bacteria isolated from volcanic permafrost exhibited polyextremotolerance, and unlike polar permafrost they included viable thermophilic prokaryotes, including methanogenic archaea and sulfur-reducing bacteria. These microorganisms are suggested to be akin to models for the alien inhabitants of Mars (Kasatkina *et al*., 2025; Mironov *et al*., 2013; Vishivetskaya *et al*., 2022).

Cryopegs – brine lenses trapped within permafrost or ice – form unique hypersaline, subzero ecosystems where the presence of free liquid water fundamentally alters microbial viability compared to

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"solid" permafrost. These highly mineralized, negative-temperature waters are the most plausible form of free water in Martian frozen soils, and the microorganisms inhabiting cryopegs likely to serve as analogs for potential Martian life (Gilichinsky *et al*., 2003). It was found, that cryopegs are inhabited with prokaryotes, mycelial fungi, and yeast belonging to aerobic and anaerobic heterotrophs, sulfate reducers, acetogens, diazotrophs and methanogens (Gilichinsky *et al*., 2003, 2005; Pecheritsyna *et al*., 2012; Shcherbakova *et al*., 2013; Spirina *et al*., 2017). Presence of halophilic and psychrophilic prokaryotes was noted as a characteristic property of these microbial communities and *in situ* metabolic activity has been demonstrated at –15°C. In general, microorganisms in frozen soils demonstrate a high potential for adaptation and survival as well as polyextremophilic traits.

Ice systems

One of the most notable studies focuses on the exploration of potential microbial life in Lake Vostok, which is buried under approximately 4 kilometers of Antarctic ice. This lake is not only the largest but also the deepest among more than 675 subglacial lakes that have been investigated using airborne radio-echo sounding and satellite altimetry surveys (Livingstone *et al*., 2022; Siegert *et al*., 2016; Wright and Siegert, 2012). Lake Vostok is located beneath the Russian Vostok Antarctic research station and has been unsealed in triplicate (Bulat, 2016).

The lake has likely to have been isolated from the surface approximately 14 million years ago, tracing back to the major East Antarctica glaciation (Bo *et al*., 2009). It is characterized by high pressure – approximately 400 bars – and *in situ* temperatures close to the freezing point of water at −2.6°C. Energy resources are severely limited due to the complete darkness and extremely low dissolved organic carbon content (DOC < 0.01 mg/L C) (Preunkert *et al*., 2011). The water in the lake is likely to be highly saturated with air, in particularly molecular oxygen, which has accumulated over long periods of duration from continuous ice melting, with a dissolved oxygen concentration estimated to be between 815 and 1300 mg/L (Lipenkov and Istomin, 2001; Lipenkov *et al*., 2016; McKay *et al*., 2003).

The Vostok Station was established in 1957, with the deepest borehole, Vostok 5G-1, being drilled on February 19, 1990. The first papers on Antarctic microbiota, focusing on microscopy and culturing, were published by S.S. Abyzov in Russian. The most notable of these papers appeared in a book published in 1993 (Abyzov, 1993). Later, Abyzov published several influential papers related to astrobiology in 1998 and 1999, following the availability of high-quality ice cores for investigation (Abyzov *et al*., 1979; 1998a, 1998b).

In his 2002 review, Abyzov suggested that microorganisms in the Vostok ice core of Central Antarctica may persist in a state of prolonged anabiosis (Abyzov *et al*., 2002). However, it is now recognized that these findings were erroneous due to contamination during those earlier studies. Recent research has shown that environmental DNA (eDNA) is ubiquitous, particularly in confined environments (Cook *et al*., 2025; Malli Mohan *et al*., 2020).

Recent studies indicate that the ice covering Lake Vostok is notably clean, with low levels of chemical and biological contamination. The uppermost layer of lake water appears to be almost entirely devoid of life, with only a few bacterial phylotypes identified in the accreted ice that are not linked to contamination (Bulat, 2016; Bulat *et al*., 2004, 2009). The DNA profile of the chemolithoautotrophic thermophile *Hydrogenophilus thermoluteolus* (philum *Pseudomonadota*) suggests the existence of a deep biosphere within the surrounding bedrock (Bulat *et al*. 2004; Lavire *et al*. 2006; Petit *et al*. 2005). However, the high levels of oxygen stress in the water might pose significant challenges for biological life (Bulat *et al*. 2004).

It has been proposed that the niche for this thermophilic microbiota lies within the deep faults of the bedrock encircling the lake. The environmental conditions in this area – including warm, anoxic, CO_2-rich sediments and potential hydrogen emissions from water radiolysis – could support such microbiota. Sporadic seismotectonic activity (Studinger *et al*. 2003) may have introduced some material from these veins into the lake and the accreted ice (Bulat *et al*. 2004; Petit *et al*. 2005).

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According to the data from Bulat *et al*. (2009), cell concentrations in both accretion ice and glacial ice would not exceed 19 to 24 cells/mL. These values are similar to those found in other studies, such as D'Elia *et al*. (2008). The environmental conditions in the lake and the accreted ice would limit the types of organisms as in chemoautotrophs. The possible redox couples appear to be restricted to hydrogen and/or sulfides as electron donors, with sulfates and oxygen (from sediment inclusions) serving as electron acceptors. Carbon dioxide or carbonate from sediments could act as a carbon source. Therefore, if life persisted in this environment, we might expect to find anaerobic chemoautotrophic piezophilic psychrophiles in the accretion ice, as well as similar organisms with a high tolerance for oxygen in the lake water, which is likely to be supersaturated with oxygen.

Aside from the thermophile found in natural accretion ice, the current bacterial findings (which underwent all necessary contamination precautions) in lake water introduced into the borehole after the lake unsealed (referred to as "technogenic," meaning contaminated lake water) include previously unknown and phylogenetically unclassified phylotypes. These belong to several groups, such as phylum Candidatus *Parcubacteria*, *Herminiimonas* of *Oxalobacteraceae* (*Betaproteobacteria,* phylum *Pseudomonadota*), and *Marinilactobacillus* of *Carnobacteriaceae* (phylum *Bacillota*). The significance of contamination-free sampling was also highlighted in the work of Bulat *et al*. (2020, 2024).

Subglacial Lake Vostok is considered as one of the only extremely clean (microbe-free) large aquatic systems on Earth. This unique environment serves as an ideal model site for searching for life on icy bodies such as Jupiter's moon, Europa, and/or Saturn's moon, Enceladus. If life is confirmed in Lake Vostok, it would enhance the likelihood of finding life on these icy moons of distant planets and planets themselves.

Arid soils

Water is a necessary solvent used by all life forms on the Earth, since all metabolic reactions require the presence of watery environments. Its low water content can limit or suppress life's physicochemical processes. It has been shown that desert soil microbial communities can withstand simultaneous actions of low pressure (0.01 Torr), low temperature (from −50 to −130°C range) and high doses of ionizing radiation (at least up to 100 kGy), preserving high cells counts, as well as high biodiversity. From this it can be extrapolated that microbial communities in such habitats can likewise remain viable under Martian and outer space environments, withstanding radiation damage for million of years (Cheptsov *et al*., 2018a, 2018b, 2018c, 2018d). Further, it has been shown that the majority of culturable heterotrophic bacteria of Sahara, Gibson and Mojave Desert soils can grow in wide temperature and pH ranges, and in high salt (including perchlorates) concentrations. Extreme tolerance levels were identified for bacteria of *Arthrobacter, Microbacterium, Bacillus, Planomicrobium, Kocuria, Leucobacter*, and *Pontibacter* genera. In addition, surprisingly, a high proportion of psychrotolerant bacteria is found in soils of hot deserts (Belov *et al*., 2018; 2019). It is demonstrated that arid soil microbial communities *in situ* are almost not inhibited by 5% sodium perchlorate. Furthermore, they are not only surviving, but are fairy active in the presence of perchlorate, with an increase in the number of metabolically active Bacteria and Archaea (Cheptsov *et al*., 2021).

Recently, Russian microbiologists renewed international collaboration on the basis of former Soviet Union states in a series of joint projects with academic institutions from Uzbekistan, China and Italy dedicated to comprehensive studies of microbial communities thriving in Central Asian hot deserts, especially on the former bottom of the Aral Sea which now represents an extremely dry and saline landscape. Currently, phylogenetic diversity of several desert soil ecotopes have been described and biocalcining and water-retaining microorganisms have been isolated from desert saline soil and characterized (Chernyh *et al*., 2024; Kondrasheva *et al*., 2023; Yakimov *et al*., 2025).

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Thermal ecosystems

Despite Russia's predominantly cold climate and the flourishing field of cryoastrobiology, a vast majority of other extreme ecosystems is also available in Russia for investigations. Most notable are the hydrothermal environments of the Kamchatka Peninsula and Kuril Islands. Here, lithotrophic, chemosynthetic microorganisms thrive at high temperatures by exploiting inorganic compounds for energy. Such organisms possess exceptional adaptive capacities to survive. These hydrothermal settings likely to mirror conditions on the early Earth when life first emerged, making hot-spring community's valuable analogs of primordial microbial ecosystems. Moreover, chemosynthesis is widely regarded as the principal metabolic mode in extraterrestrial habitats deprived of sunlight. The volcanically active Kamchatka region thus serves as a singular modern theater for the evolution of extremophiles, which in turn act as pivotal geochemical agents in these habitats.

Volcanic activity heats Kamchatka's spring waters to boiling point, dissolving heavy and ostensibly toxic elements – arsenic, cadmium, lead, mercury – together with vital iron and sulfur minerals, creating pH extremes that can range from 0–2 to 9–10 (Karaseva *et al*., 2024; Kochetkova *et al*., 2022; Lebedeva and Kharitonova, 2020).

Pioneering investigations into Kamchatka's microbial communities were conducted by G.A. Zavarzin, E.A. Bonch-Osmolovskaya, V.F. Galchenko and their colleagues at the Winogradsky Institute of Microbiology RAS (Bonch-Osmolovskaya *et al*., 1999; Dvoryanchikova *et al*., 2011; Zavarzin, 1973), followed by wide international collaborative efforts of 1996–2010 which involved world-known experts in extreme microbiology, such as Karl Stetter, Juergen Wiegel and many others.

Under Zavarzin's guidance, new microbial taxa were described, the principal biochemical pathways in hydrothermal vents were elucidated, key trophic links in these communities were established, and microorganisms' direct roles in geochemical processes – particularly in shaping Earth's atmospheric composition – were proposed (Gerasimenko *et al*., 1983; Zavarzin and Karpov, 1982; Zavarzin *et al*., 1989). Notably, the group of Academician Zavarzin described novel chemosynthetic processes which could greatly influence both the lithosphere and atmosphere of the early Earth–autotrophic dissimilatory reduction of iron minerals with H_2 as the only electron donor, CO_2 as the only carbon source (Balashova and Zavarzin, 1979), and the process of autotrophic hydrogenotrophic carboxydotrophy with a proton being the electron acceptor (Svetlichny *et al*., 1991).

E.A. Bonch-Osmolovskaya's team succeeded the pioneering works of Zavarzin and isolated dozens of novel thermophilic and hyperthermophilic archaea and bacteria from both terrestrial and marine hydrothermal systems as well as subsurface thermal habitats, including representatives of deep phylogenetic lineages at the order, class and phylum levels. They also characterized the diversity of key metabolic groups which could drive the biogeochemical processes in terrestrial hot environments (Chernyh *et al*., 2015; Frolov *et al*., 2021, 2023a, 2023b; Kublanov *et al*., 2017; Merkel *et al*., 2016; Podosokorskaya *et al*., 2013). They characterized new metabolic types utilizing hydrothermal energy sources and oxidants, sequenced complete genomes of these thermophiles to define their metabolic capabilities, and identified thermostable enzymes with biotechnological potential (Bonch-Osmolovskaya, 2013; Bonch-Osmolovskaya *et al*., 1988, 1999; Merkel *et al*., 2016, 2017). Of special importance is the description within a wide international collaborative project of the novel lithotrophic metabolic process which is only thermodynamically favorable at elevated temperatures, that is formate-driven growth coupled with H_2 production (Kim *et al*., 2010).

V.F. Galchenko's laboratory examined carbon and sulfur biogeochemical cycling in extreme marine, lacustrine and terrestrial ecosystems using physico-chemical, radioisotope and microbiological diagnostic methods. They investigated methanotrophic bacteria's role in regulating atmospheric methane and devised the Life Research Program for Europa, Jupiter's icy moon (Galchenko, 2001, 2002).

The physiology and adaptive strategies of Kamchatka microorganisms were further explored by research teams in Siberia and the Russian Far East (Bryanskaya *et al*., 2015; Peltek *et al*., 2020; Rozanov *et al*., 2014).

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During a joint Russian–American expedition project "Kamchatka Microbial Observatory" of 2003–2008, the fate of various organic compounds in natural hydrothermal vents were studied: key biomolecules were found to dissolve, desorb or bind to mineral surfaces (Deamer *et al*., 2006, 2019). Investigations of oil seeps in Uzon Caldera's central zone confirmed their biological origin (Galimov *et al*., 2015; Simoneit *et al* 2009).

Subsequent laboratory experiments, conducted under the "hot" origin-of-life paradigm, analyzed organic matter from hot springs and steam-gas outlets. These studies revealed crucial prebiotic constituents – nitrogenous compounds (amino acids, nitriles, amides, nitrogen cycles) and lipid precursors (carboxylic acids, esters, alcohols, aldehydes) – supporting hypotheses of thermally driven biochemical evolution (Kompanichenko, 2019; Kompanichenko *et al*., 2010, 2016; Poturay and Kompanichenko 2019).

Salty ecosystems

Another ecosystem that can be considered as a model ecosystem in the context of astrobiology research are the saline alkaliphilic lakes in Transbaikalia, whose microbial composition includes organisms that can survive and develop in conditions of increased concentrations of mineral salts and high pH. Transbaikalia is located in the cryo-arid climate zone, which is characterized by sharp fluctuations in seasonal and daily temperatures and low precipitation. Therefore, in soda lakes, salts accumulate not only due to evaporative concentration during hot and dry periods, but also during freezing in winter. Intensive microbiological studies of lakes are due to interest in them, in particular, as relic systems, possible places of origin of life and terrestrial biodiversity, as well as an extreme ecosystem with the existence of a specific alkali-halophilic microbial community (Zavarzin, 1993). Microbiologists G. Zavarzin, V. Gorlenko, B. Namsaraev, and D. Sorokin made a huge contribution to the study of salt ecosystems (Namsaraev, 2008, 2009; Sorokin *et al*., 2014; Zavarzin, 2007). As a result of many years of research, pure cultures of more than 30 representatives of cyanobacteria and more than 70 strains of representatives of bacteria of different physiological groups were isolated and described (Gorlenko, 2007; Namsaraev *et al*., 2018; Tsyrenova *et al*., 2011 and others). The dominant phyla in microbial communities of all these lakes are *Proteobacteria* (*Pseudomonadota*) (30–52%), *Firmicutes* (*Bacillota*) (5–20%), *Bacteroidetes* (*Bacteroidota*) (11–24%), with differences at the class and genera level. The exception was the highly mineralized Lake Borzinskoye, where a significant proportion of *Euryarchaeota* archaea (currently reclassified as the phylum *Methanobacteraeota*) (33%) was identified. A common feature of the microbial communities of mineral lakes is a significant proportion of bacteria involved in different stages of the sulfur biogeochemical cycle (Lavrentyeva *et al*., 2023; Zaitseva *et al*., 2014, 2018). The main role in the production of autochthonous organic matter belongs to cyanobacteria, the proportion of anoxygenic photosynthesis in most lakes did not exceed 14.2% of the total photosynthesis. The main process of anaerobic destruction of organic matter in lakes is sulfate reduction. Importantly, mineralization determines the type of relationship between production and destruction processes. If in weakly mineralized reservoirs, the rates of processes are relatively high and the processes are most likely balanced, then in highly mineralized reservoirs the productivity is high and sulfate reduction is minimal. Perhaps as result of this imbalance, organic matter can accumulate in highly mineralized lakes. This process can also be facilitated by the burial of organic matter as a result of seasonal salt precipitation in highly mineralized lakes (Namsaraev, 2009; Namsaraev and Namsaraev, 2007; Namsaraev *et al*., 2015).

Additionally, saline lakes of the Altai region can also be considered as analogs of Martian ecosystems with low temperatures and high salt content solutions. Viability of both halophilic archaea and halotolerant bacteria from these lakes only slightly decreased in conditions that hypothetically existed in subsurface layers of the early Mars (Bryanskaya *et al*., 2020).

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Search for extraterrestrial intelligence

The founder of the initial scientific abstraction of SETI in Russia/Soviet Union was the astrophysicist I.S. Shklovsky. At first, he published a large article titled "Is it possible to communicate with intelligent beings of other planets" in the scientific-popular magazine Priroda ("Nature" in Russian) (Shklovsky, 1960), which formed the basis of his famous book Universe, Life, Intelligence (Shklovsky, 1987) that was re-published in Russian six times. In this book he provided a rationale for habitable zones, and also assessed the probability of discovering life and intelligent life elsewhere in the Universe. Shklovsky collaborated with Carl Sagan and later published a joint book titled: "Intelligent Life in the Universe" (Shklovsky and Sagan, 1998). At that time, this work influenced the development of similar research throughout the world. Work on the SETI program was continued by Shklovsky's students. N. Kardashev has formulated the idea of the existence of three types of civilizations (Kardashev, 1964) and together with colleagues presented the concept of the "radio-communicational" strategy of SETI (Kardashev, 1978). Subsequently, the Radio Astronomy Council of the USSR Academy of Sciences established a dedicated section titled "Search for Extraterrestrial Civilisations."

Currently, work within the framework of SETI in Russia is also continued by Shklovsky's followers (Gindilis and Gurvits, 2019; Panov *et al*., 2021, 2025).

Global trends in the development of astrobiology

Astrobiology is a fundamental discipline of a wide range of scientific subjects, and its research programs are aimed at future discoveries and should, in the first instance, be primarily directed at government and public–private funding sources.

As for many natural sciences, the main attributes of astrobiology are the experimental methodologies for acquiring knowledge, collecting and analyzing actual material and datasets, which involves the development of a new ways of moving forward, as well as determining new research questions and organizing expeditions and space missions.

Until recently, primary way for astrobiologists to obtain results was working within broader scientific programs in related fields, where astrobiology research was incorporated as a component and the resulting data were subsequently integrated into a unified astrobiology concept.

Over the past two decades, the global community of astrobiologists has actively worked to combine efforts and structure research within an independent astrobiology framework, establishing dedicated research programs, funding mechanisms, and organizational measures. It should be noted that G.A. Tikhov pointed out the great scientific prospects of astrobiology and the importance of its further development back in 1956, when he wrote about the need to create an astrobiology institute: "*There is a pressing need to create a special astrobiology institute that would concentrate the efforts of astronomers, physicists, chemists, botanists, microbiologists, biologists of various profiles, etc. The institute should have an astronomical observatory and a chemical laboratory equipped with the latest technology, and organize expeditions to various places on the globe. There can be no doubt that a wide field of research is open to the new science*" (Tikhov, 1956).

All these ideas are currently being actively implemented in the United States of America and the European Union, in the form of the NASA Astrobiology Institute – NAI (1998) and the European Astrobiology Institute – EAI (2019), respectively. The European Astrobiology Network Association – EANA has been highly active in promoting astrobiology since 2001. Common activities are organizing research, creating, and integrating working groups of astrobiologists from various fields, developing scientific and educational programs, including the organization of expeditions, workshops and summer schools. Astrobiologists are actively involved in writing scientific projects that compete with projects from other scientific fields for the same funding source. The most important tool for integrating astrobiologists is regular participation in national and international conferences and symposiums, where ideas are exchanged, research results are presented, and future development prospects are discussed. An

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important aspect of the development of the Western astrobiology is the financial support from space agencies – ESA in Europe and NASA in USA.

Astrobiology institutes are virtual organizations that bring laboratories from various universities or research institutes, where astrobiology-related work is conducted and financial support for these activities is provided.

The names of the working groups within the EAI reflect the priority areas of research in Western astrobiology. These include the study of the formation and evolution of planetary systems and the search for habitable worlds; prebiotic synthesis and the complexities of the origin and evolution of life; investigations of exoplanetary ecosystems and the conditions for their potential habitability; studies of terrestrial life in extreme environments; the identification and search for biosignatures beyond Earth; as well as historical, philosophical, social, and ethical issues in astrobiology. An important event for European astrobiologists was the approval of the first joint project AstRoMap: "Astrobiology and Space Missions Road Mapping" (2013–2015) within the Seventh Framework Programme for Research and Innovation (FP7) with the aim of developing a roadmap for European research in the field of astrobiology (Horneck *et al*., 2016), as well as the COST Action TD1308: Origins and evolution of life on Earth and in the Universe (ORIGINS) project (2014–2017), which involved almost 200 researchers from 30 countries and which provided European researchers with opportunities for interdisciplinary networking. This made it possible to form working groups and begin organizing expeditionary research and holding seminars. A website site has been developed and is currently operating, which is necessary for providing information to specialists and all those interested in the complexities of astrobiology. Vacancies for students and young scientists for developing their careers in the field of astrobiology are also posted there.

Additionally, project of organizing summer schools where young astrobiologists – aimed at enhancing their qualifications – has also been approved. Regular workshops within the framework of the AbGradE (Astrobiology Graduates in Europe) organization, the goal of which is to inspire, educate future students of astrobiology, early career scientists and open up connections between these cohort of scientists in astrobiology, space science and other related fields.

Across Europe, several universities have incorporated astrobiology into their teaching programs, each adapting the course content to reflect their own areas of emphasis. Given the wide range of topics encompassed by astrobiology, institutions select and integrate individual modules – focused on biology, chemistry, geology, or related disciplines – that align with their particular strengths. Textbooks on astrobiology are published regularly (Cockell, 2020; Kolb, 2019; Plaxco and Gross, 2021).

In Germany, the National Astrobiology Society is active, uniting various institutions, which undertake both the organization of national conferences on astrobiology and the coordination of scientific research by supporting for students.

The main criterion for the success of the activities of Western astrobiologists is the recognition of astrobiology by the scientific community as a relevant independent research area, competitive and promising with the possibility of funding on an equal footing with other priority scientific areas, although astrobiologists will need to constantly prove this point with their achievements.

Prospects for the development of astrobiology in Russia

Astrobiology in Russia is currently becoming gradually aligned with various scientific groups and has begun to coordinate inter-research programs.

Cooperation between astrobiologists is largely achieved through their regular interaction to air and share ideas at meetings and conferences, both nationally and internationally. Scientists have to organize themselves into groups of special interest so as to visit one another's labs and even go on expeditions to sites of special scientific interest.

In addition to three mentioned earlier Russian institutions that organize regular conferences for the exchange of scientific information between astrobiologists, a number of national research institutes

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organize seminars at which various studies in the astrobiology field are periodically discussed. There are also groups of researchers who are engaged in astrobiology or related fields quite separately. The Scientific Council of Astrobiology of the Russian Academy of Sciences (RAS) is coordinating different organizational activities.

An important aspect of astrobiology's development in Russia and globally is the engagement of specialists whose research intersects astrobiological questions, even if they do not formally label their findings as such. Inviting these experts to contribute to astrobiology conferences and to participate in joint scientific projects is crucial and offers significant promise for enhancing the field's scientific potential.

A further essential condition for the sustainable advancement of any modern scientific discipline is the synergy between research, education and practical application – for example, through the commercialization of innovative ideas. This relationship is embodied in the well-known knowledge-triangle concept, and the stronger the interactions within that triangle, the more sustainable the field (Unger and Polt, 2017).

With regard to astrobiology, the most important component for its development is the field of education. At present, conditions already exist for the introduction of astrobiology courses into university curricula for training specialists at the master's level, the need for which is gradually but steadily increasing. The first step in this direction is the publication of the textbook of Astrobiology in Russian for students at Dubna State University, developed for the profile of the Master's program which includes "Radiation Biophysics and Astrobiology," where astrobiology itself is taught as a tag-on subject (Rozanov and Saprykin, 2024). However, much work remains to be done in developing and disseminating astrobiology courses within Russia's educational landscape. Consolidated participation of astrobiologists having expertise in different scientific fields is necessary to create a comprehensive astrobiology curriculum. The experience of Western universities, if adapted to the specific context and needs of Russian education, could prove highly valuable in advancing such efforts.

More complex aspects are innovative developments that could enable astrobiologists to gain significant financial independence, since the main financial support is provided by government institutions. However, there is an opportunity to combine fundamental and practical areas of activity. The instrumental base of astrobiologists and, above all, innovative developments for the study and detection of biological objects beyond the Earth, can be successfully applied to terrestrial ecosystems, for example, in such areas as ecology or medicine. Currently, practical astrobiology is being formed, which studies the adaptive potential of terrestrial organisms in artificial space ecosystems – in a spacecraft and on lunar stations of the near future, as well as biotechnological processes in space conditions.

In the contemporary context, the use of electronic resources is of critical importance for the effective exchange of scientific information, the dissemination of vacancy announcements in astrobiological research, the discussion of joint projects, the organization of online conferences, and the prompt resolution of emerging issues, as well as for participation in various international communities, including astrobiology associations

One such organization is the Network of Researchers on the Chemical Emergence of Life (NoRCEL), founded by Dr Sohan Jheeta in 2013. It has since evolved into the NoRCEL Institute (https://norcel.net/), which now oversees a suite of groundbreaking initiatives.

The AstroScience Exploration Network (ASEN) operates across the African continent, while the Latin America Hub (LatAm Hub) serves Latin American communities; both deliver online science education with a focus on astroscience. The Blue Earth Project (BEP) addresses pressing terrestrial issues, and their Microbial World Network (MWN) adopts a top-down approach to trace life's origins – starting from prokaryotes, in particular the domain of Archaea, and working back towards prebiotic chemistry. Through NoRCEL Education and Research Academy (NoRCEL ERA), the Institute extends its online astroscience programs throughout the Global South. Russian scientists also participate regularly in NoRCEL events, especially in MWN enriching its international collaborations.

Finally, to increase interest in the challenges that astrobiology deals with, it is important to publish books, popular science articles, general educational lectures, stand-alone chapters in a collective book,

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and interviews in the mass media (Kotsyurbenko and Govorova, 2024, Nikitin, 2012, https://www.youtube.com/@surdinpodcast).

International cooperation has always been an important factor for the development of Russian astrobiology. A significant event for Russian astrobiologists was the organization of the EANA 2010 conference with broad international participation, including representatives from both Europe, USA and further afield. Further, international scientific cooperation developed in various areas, the key ones being realized in astrochemistry, space biology and medicine, space missions aiming at the search for life and study of extreme terrestrial ecosystems relevant to astrobiology (Table 4).

The main objective of the Bion-M2 program (Figure 11) is a comprehensive study of the combined biological effects of weightlessness and high levels of cosmic radiation on the body at the systemic, organ, cellular and molecular levels. The biosatellite was launched into an orbit of approximately 400 kilometers, which is as high as the orbit of the ISS and 5 times higher in radiation levels than the first Bion.

Dosimetric equipment will allow measurements of the dynamics of the dose rate of ionizing cosmic radiation not only inside but also outside the device and will allow the separation of the received doses of cosmic radiation by components (the contribution of electrons, protons, neutrons and heavier charged particles).

In the Regulation of the Scientific Council of Astrobiology of RAS from 2020, one of the objectives of its activities is to strengthen and develop international relations with scientists working in the field of astrobiology.

In Russia, the new national space program has been approved in 2025. It includes various space activities, in particular, the ambitious project of lunar exploration in collaboration with China and other countries. A few Russian automatic spacecrafts will explore lunar surface (Table 4). Russia is also developing a new human rated spacecraft designed for flights beyond low Earth orbit. In the framework of the project of the International Lunar Research Station, biological and medical experiments are also planned. They should include studying bioavailability and bio-toxicity of lunar regolith, developing plant cultivation methods in it and studying symbiotic relationships of plants with microbial communities, testing small-scale terrestrial ecosystems on lunar surfaces as well as studying long-term ionizing radiation and zero magnetic field effects on plant growth and development.

An important aspect of international cooperation in space is the work of the COSPAR scientific commissions on planetary protection, which include representatives from Russia (https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-planetary-protection-ppp/). The main goals of these commissions are to prevent contamination by alien biological material and to develop the appropriate standards for protection against such contamination.

As things stand, modern astrobiology in Russia faces challenges, and most significant one is the lack of necessary financial support. The Russian space program has been historically underfunded, which impacts its ability to conduct extensive astrobiological research. The budget constraints mean that progress can be slow, with many ambitious projects facing delays or cancelations.

Unfortunately, as a result of the difficult political situation, cooperation with Western scientists was suspended, and promising space programs were terminated. Additionally, political tensions have complicated international scientific collaboration. Issues such as the International Traffic in Arms Regulations (ITAR) pose challenges for cooperative research efforts involving foreign scientists.

Against this backdrop, contemporary astrobiology in Russia is undergoing a process of reorganization and diversification. The Scientific Council for Astrobiology of the Russian Academy of Sciences has succeeded in establishing astrobiology as an independent and fully-fledged scientific discipline within the Academy as the main funding organization. Russian astrobiologists are forced to redirect cooperation towards other countries, such as China and India´ and further follow the trends of other scientific fields in Russia to establish and/or renew scientific collaboration with other BRICS-member countries, etc. However, the process of establishing new scientific relationships may take a long time. There is, however, hope that the previous effective scientific collaborations can be restored in future.

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Table 4. *Key modern national and international projects related to astrobiology*

№	Topics	Dates of cooperation	Russian partner	Foreign partner	Status
1	Orbital experiments: influence of space factors on various organisms				
	PHOTON and	1995–2013	Roscosmos,	ESA and	Completed
	BION series	2025	IMBP, Moscow	researchers from	In progress
	BION M-2	2027	Roscosmos,	Europe and	Planned
	(Figure 11)	2030	IMBP, Moscow	China	Planned
	Russian Orbital Service Station (ROS)		Roscosmos, IMBP, Moscow	– –	
	BION M-3		Roscosmos, IMBP, Moscow	–	
2	Origin of Life: Joint expedition to Kamchatka – biogeochemistry and ecology of thermal springs	2001–2004	Institute of Volcanology and Seismology in Petropavlovsk, Institute for Complex Analysis in Birobidzhan	University of California at Santa Cruz, NASA AIMS, University of Oregon, Carnegie Institution of Washington	Completed
3	Cryosystems: «Vostok» Lake	2004–2024	Petersburg Nuclear Physics Institute	University Grenoble Alpes, CNRS, France	Completed
4	Astrochemistry: synthesis of prebiotic compounds under proton irradiation	2010–2022	Joint Institute for Nuclear Research, Dubna	*Sapienza University of Rome*, Italy University of Tuscia, Viterbo, Italy	Completed
5	Extreme ecosystems: Kamchatka – thermophiles	2015–present	Russian Science Foundation projects	–	in progress
6	Space missions:	2012–2022	Roscosmos	ESA	Canceled
	ExoMars –	Initial stage	Roscosmos	NASA	Canceled
	searching for life	2019–2021	Roscosmos	–	Planned
	on Mars	Final stage	ROSCOSMOS	China	Planned
	Venera-D:	2034–2036	ROSCOSMOS	China	Planned
	Searching for life	2028	ROSCOSMOS	China	Planned
	in Venusian	2029	ROSCOSMOS	China	Planned
	clouds	2030			
	Moon exploration: Luna-26, landing	2035–2040			

(*Continued*)

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Table 4. (*Continued*)

№	Topics	Dates of cooperation	Russian partner	Foreign partner	Status
	mission Luna-27A, landing mission Luna-27B, landing mission Lunar space base				
7	Deep space studies: exoplanets, extraterrestrial organic matter etc. by space telescopes: Spektr RG Spektr-UV, Millimetron	2019 2026 2026	ROSCOSMOS, Space research Institute	DLR, Germany – –	Partly canceled Planned planned

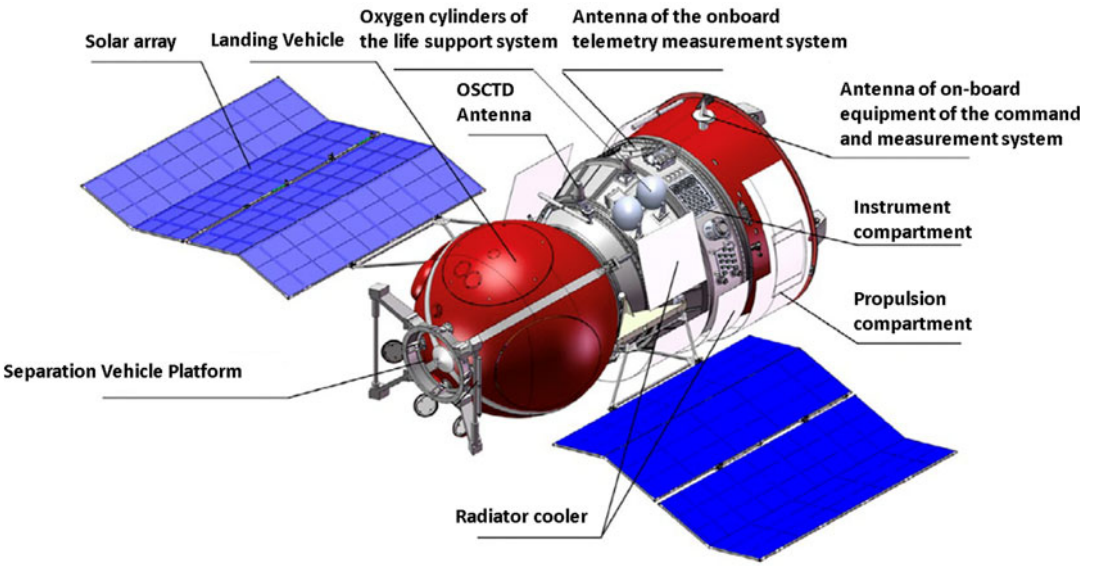


Figure 11. *Scheme of "Bion-M2". OSCTD – Onboard synchronizing coordinate-time device.*

Conclusion

Russian astrobiology as a science emerged in the mid-20th century, building on the body of space-related knowledge accumulated by that time and shaped by the scientific and philosophical ideas of the founders of Russian cosmism. Their intellectual legacy provided a broad foundation for subsequent research into life as a cosmic phenomenon, explored in all the diversity of its manifestations.

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The achievements of Russian scientists and the rapid development of space technology during the USSR era contributed to the gradual development of astrobiology research and its differentiation into various subjects and sub-subjects. Presently, Russian astrobiology is following the path of interaction between scientific research groups, but is in great need of government financial support for its further development. Russian astrobiology is now forced to diversify its activities and establish new scientific relationships. Difficulties during the previous few decades, lack of effective cooperation and new modern political challenges have to be overcome by close collaboration of Russian astrobiological groups, creating joint competitive projects and contributing to prospective space programs with astrobiological goals.

The peculiarity of astrobiology associated with the need to integrate various science subject matters and search for scientific truth in their interaction has an important ideological component, which was enshrined by Academician Tikhov in the form of following quote: *"The close connection of astrobiology with astronomy, physics, chemistry, biology will unite the efforts of researchers. All this will give science a unified set of knowledge about life on Earth and other planets. And in the future… truly unlimited possibilities will open up for astrobiology. The secrets of life on other planets will be available to humanity. The study of life on Earth and on other planets will merge together"* (Tikhov, 1953).

Having emerged as a science encompassing wide coverage of topics and questions – both scientific and ideological – addressed by researchers from diverse perspectives, astrobiology experienced a period of certain skepticism on the part of the scientific community (Nascimento-Dias and Martinez-Frias, 2023). Today, however, it has regained recognition as a discipline of global integrative character (Malaterre and Lareau, 2023). In the modern world – in particular scientific views of developed countries – in line with the understanding of astrobiology as a discipline that integrates diverse area of natural sciences, the concept of coevolution is gaining prominence. This idea emphasizes the joint development of humanity and nature as interconnected processes.

The ideas of partnership – rather than ownership of it – and the challenges of global ecology are becoming significant, which is absolutely consistent with the basic provisions of cosmism and involves the creation of scientific concepts and ideological ideas aimed at overcoming inertial anthropocentric views of the world.

Finding a common language between scientists working in different fields, often having different types of scientific viewpoint and using different methodological approaches to obtaining results, is a powerful tool for fruitful cooperation between scientists and all those who are interested in this area of knowledge. From this viewpoint, we can conclude that astrobiology is a science that stands as a leader in both promising breakthroughs and integrative processes within the modern global scientific community. Moreover, it exerts a positive influence on the worldview of humanity as a whole.

The Russian astrophysicist and science popularizer, namely I. Shklovsky pointed out that intelligent life in the Universe can be an unusually rare, if not unique, phenomenon and therefore "the greater responsibility falls on humanity so that this spark of consciousness, due to its unreasonable actions, does not go out, but flares up into a bright fire, observable even from the distant outskirts of our Galaxy" (Shklovsky, 1987).

Russia, with its considerable scientific potential – particularly in the field of space research – and its rich philosophical and cultural-historical heritage in the study of knowledge of the world, is well positioned to make a significant contribution to global astrobiology. The establishment of a dedicated Russian astrobiology institute in the near future would be an excellent opportunity to structure and coordinate the scientific work of Russian astrobiologists, while also opening new international frontiers for cooperation with all colleagues across the globe.

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References

Abramov A, Vishnivetskaya T and Rivkina E (2021) Are permafrost microorganisms as old as permafrost?. *FEMS Microbiology Ecology* **97**, fiaa260. https://doi.org/10.1093/femsec/fiaa260

Abyzov SS, Bobin NE and Koudriashov BB (1979) Microbiological flora as a function of ice depth in central Antarctica. *Life Sciences in Space Research* **17**, 99–103. https://doi.org/10.1016/b978-0-08-023416-8.50016-7

Abyzov SS (1993) Microorganisms in the Antarctic ice. In Friedmann EI (ed), *Antarctic Microbiology*, Wiley Series in Ecological and Applied Microbiology. New York: Wiley-Liss, pp. 265–295.

Abyzov SS, Mitskevich IN and Poglazova MN (1998a) Microflora of the Deep Glacier Horizons of Central Antarctica. Microbiology (in Russian).

Abyzov SS, Mitskevich IN, Poglazova MN, Barkov NI, Lipenkov VY, Bobin NE, Koudryashov BB and Pashkevich VM (1998b) Antarctic ice sheet as a model in search of life on other planets. *Advances in Space Research* **22**, 363–368. https://doi.org/10.1016/S0273-1177(98)00194-X

Abyzov SS, Welsh M, Vestal F, Vorobyova EA, Heptner AR, Gerasimenko LM, Gilichinsky DA, Zhegallo EA, Zavarzin GA, Zvyagintsev DG, Orleanskiy VK, Raaben ME, Rozanov AY, Sergeev VN, Soina VS, Ushatinskaya GT, Hoover R and Shkolnik EL (2002) *Bacterial Paleontology*, Rozanov AY (ed). Moscow: Paleontol. Inst. Ross. Akad. Nauk. ISBN: 978-5-907366-01-5.

Afanasyeva AN, Kapralov MI and Rozanov AY (2024) Paleontological aspect of astrobiology. *Paleontological Journal* **58**(S1), S25–S56. https://doi.org/10.1134/S0031030124601415.

Akabori S, Okawa K and Sato M (1956) Introduction of side chains into polyglycine dispersed on solid surface. *Bulletin of the Chemical Society of Japan* **29**(5), 608–611, https://doi.org/10.1246/bcsj.29.608.

Altstein AD (1987) On origin of the genetic system: The progene hypothesis. *Molecular Biology (in Russian)* **21**, 309–322.

Altstein AD (2015) The progene hypothesis: The nucleoprotein world and how life began. *Biology Direct* **10**, 67. https://doi.org/10.1186/s13062-015-0096-z.

Aniskina TS, Sudarikov KA, Levinskikh MA, Gulevich AA and Baranova EN (2023) Bread wheat in space flight: Is there a difference in Kernel quality?. *Plants* **13**(1), 73. https://doi.org/10.3390/plants13010073.

Balashova VV and Zavarzin GA (1979) Anaerobic reduction of ferric iron by hydrogen bacteria. *Mikrobiologiia. (In Russian)* **48**(5), 773–778.

Beaty DW, Clifford SM, Borg LE, Catling DC, Craddock RA, Marais DJD, Farmer JD, Frey HV, Haberle RM, Mckay CP, Newsom HE, Parker TJ, Segura T and Tanaka KL (2005) Key Science questions from the second conference on early Mars: Geologic, hydrologic, and climatic evolution and the implications for life. *Astrobiology* **5**, 663–689. https://doi.org/10.1089/ast.2005.5.6

Belov AA, Cheptsov VS, Manucharova NA and Ezhelev ZS (2020a) Bacterial communities of Novaya Zemlya archipelago Ice and permafrost. *Geosciences* **10**, 67. https://doi.org/10.3390/geosciences10020067

Belov AA, Cheptsov VS and Vorobyova EA (2018) Soil bacterial communities of Sahara and Gibson deserts: Physiological and taxonomical characteristics. *AIMS Microbiology* **4**, 685–710. https://doi.org/10.3934/microbiol.2018.4.685

Belov AA, Cheptsov VS, Vorobyova EA, Manucharova NA and Ezhelev ZS (2019) Stress-tolerance and taxonomy of culturable bacterial communities isolated from a central Mojave dessert soil sample. *Geosciences* **9**, 166. https://doi.org/10.3390/geosciences9040166

Belov AA, Cheptsov VS, Vorobyova EA, Manucharova NA and Ezhelev ZS (2020b) Culturable bacterial communities isolated from Cryo-Arid soils: Phylogenetic and physiological characteristics. *Paleontological Journal* **54**, 903–912. https://doi.org/10.1134/S0031030120080043

Belozersky AN (1957) On the species specificity of nucleic acids in bacteria. In Oparin AI (ed), *The Origin of Life on Earth*. Moscow: Publ. of the USSR Academy of Sciences, pp. 198–205.

Belozersky AN (1959) On the species specificity of the nucleic acids of bacteria. In Oparin AI, Pasynskii AG, Braunshtein AE, Pavlovskaya TE, Clark F and Synge RLM (eds), *The Origin of Life on the Earth*. London – New York – Paris – Los Angeles: Pergamon Press, pp. 322–331.

Belyaev DA, Montmessin F, Bertaux J-L, Mahieux A, Fedorova AA, Korablev OI, Marcq E, Yung YL and Zhang X (2012) Vertical profiling of SO_2 and SO above Venus’ clouds by SPICAV/SOIR solar occultations *Icarus* **217**(2), 740–751. https://doi.org/10.1016/j.icarus.2011.09.025

Berezhnoy AA, Belov GV and Wöhler C (2024) Chemical processes during collisions of meteoroids with the Moon. *Planetary and Space Science* **249**, 105942. https://doi.org/10.1016/j.pss.2024.105942

Berezhnoy AA and Borovička J (2010) Formation of molecules in bright meteors. *Icarus* **210**, 150–157. https://doi.org/10.1016/j.icarus.2010.06.036

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Berezhnoy AA, Hasebe N, Hiramoto T and Klumov BA (2003) Possibility of the presence of S, SO_2, and CO_2 at the poles of the Moon. *Publications of the Astronomical Society of Japan Nihon Tenmon Gakkai* **55**, 859–870. https://doi.org/10.1093/pasj/55.4.859

Berezhnoy AA, Kozlova EA, Sinitsyn MP, Shangaraev AA and Shevchenko VV (2012) Origin and stability of lunar polar volatiles. *Advances in Space Research, Lunar Exploration - I* **50**(12), 1638–1646. https://doi.org/10.1016/j.asr.2012.03.019

Betts BH, Warmflash D, Fraze RE, Friedman L, Vorobyova E, Lilburn TG, Smith A, Rettberg P, Jönsson KI, Ciftcioglu N, Fox GE, Svitek T, Kirschvinck JL, Moeller R, Wassmann M, Berger T (2019) Phobos LIFE (living interplanetary flight experiment). *Astrobiology* **19**, 1177–1185. https://doi.org/10.1089/ast.2018.1904

Bibring J-P, Langevin Y, Mustard JF, Poulet F, Arvidson R, Gendrin A, Gondet B, Mangold N, Pinet P, Forget F, OMEGA Team, Berthé M, Gomez C, Jouglet D, Soufflot A, Vincendon M, Combes M, Drossart P, Encrenaz T, Fouchet T, Merchiorri R, Belluci G, Altieri F, Formisano V, Capaccioni F, Cerroni P, Coradini A, Fonti S, Korablev O, Kottsov V, Ignatiev N, Moroz V, Titov D, Zasova L, Loiseau D, Pinet P, Doute S, Schmitt B, Sotin C, Hauber E, Hoffmann H, Jaumann R, Keller U, Arvidson R, Duxbury T and Neukum G (2006) Global mineralogical and aqueous Mars history derived from OMEGA/Mars express. *Data Science* **312**(5772), 400–404. https://doi.org/10.1126/science.1122659

Bo S, Siegert MJ, Mudd SM, Sugden D, Fujita S, Xiangbin C, Yunyun J, Xueyuan T and Yuansheng L (2009) The Gamburtsev mountains and the origin and early evolution of the Antarctic Ice Sheet. *Nature* **459**, 690–693. https://doi.org/10.1038/nature08024

Bonch-Osmolovskaya EA (2013) New thermophilic prokaryotes. *Priroda* **9**, 34–41.

Bonch-Osmolovskaya EA, Miroshnichenko ML, Slobodkin AI, Sokolova TG, Karpov GA, Kostrikina NA, Zavarzina DG, Prokofieva MI, Rusanov II and Pimenov NV (1999) Biodiversity of anaerobic lithotrophic prokaryotes in terrestrial hot springs of Kamchatka. *Microbiology (in Russian)* **68**, 398–406.

Bonch-Osmolovskaya EA, Slesarev AI, Miroshnichenko ML, Svetlichnaya TP and Alekseev VA (1988) Characteristics of Desulfurococcus amylolyticus sp. nov. – A new extremely thermophilic archaebacterium isolated from the hydrothermal vents of Kamchatka and Kunashir Island. *Microbiology (in Russian)* **57**, 94–102.

Borshcheva K, Fedoseev G, Punanova AF, Caselli P, Jiménez-Serra I, Vasyunin AI (2025) Formation of complex organic molecules in prestellar cores: The role of non-diffusive grain chemistry. *The Astrophysical Journal* **990**(2), id.163, 25. https://doi.org/10.3847/1538-4357/adea73.

Briot D (2012) A possible first use of the word astrobiology? *Astrobiology* **12**(12), 1154–1156. https://doi.org/10.1089/ast.2012.0896.

Bryanskaya AV, Berezhnoy AA, Rozanov AS, Serdyukov DS, Malup TK and Peltek SE (2020) Survival of halophiles of Altai lakes under extreme environmental conditions: Implications for the search for Martian life. *International Journal of Astrobiology* **19**, 1–15. https://doi.org/10.1017/S1473550419000077

Bryanskaya AV, Rozanov AS, Slynko NM, Shekhovtsov SV and Peltek SE (2015) Geobacillus icigianus sp. nov., a thermophilic bacterium isolated from a hot spring. *International Journal of Systematic and Evolutionary Microbiology* **65**, 864–869. https://doi.org/10.1099/ijs.0.000029

Bulat SA, Anosova OI, Tsvetkova AY and Shvetsov AV (2024) The uppermost water horizon of subglacial Lake Vostok could be microbial DNA-free, as shown by Oxford Nanopore sequencing technology. *Arctic and Antarctic Research* **70**, 554–564. https://doi.org/10.30758/0555-2648-2024-70-4-554-564

Bulat SA (2016) Microbiology of the subglacial Lake Vostok: First results of borehole-frozen lake water analysis and prospects for searching for lake inhabitants. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* **374**, 20140292. https://doi.org/10.1098/rsta.2014.0292

Bulat SA, Alekhina IA, Blot M, Petit JR, De Angelis M, Wagenbach D, Lipenkov VY, Vasilyeva LP, Wloch DM, Raynaud D and Lukin VV (2004) DNA signature of thermophilic bacteria from the aged accretion ice of Lake Vostok, Antarctica: Implications for searching for life in extreme icy environments. *International Journal of Astrobiology* **3**, 1–12. https://doi.org/10.1017/S1473550404001879

Bulat SA, Alekhina IA, Lipenkov VY, Lukin VV, Marie D and Petit JR (2009) Cell concentrations of microorganisms in glacial and lake ice of the Vostok ice core, East Antarctica. *Microbiology* **78**, 808–810. https://doi.org/10.1134/S0026261709060216

Bulat SA, Bulat ES, Grokhovsky VI, Muftakhetdinova RF, Kolunin RN, Tselmovich VA, Sekatski SK, Smirnov AA, Ekaykin AA and Petit J-R (2018a) Search for Antarctic micrometeorites in Blue Ice field, Lomonosov mountains, Voltat Massive, Queen Maud Land, East Antarctica. 81st Annual Meeting of The Meteoritical Society, p. 6138.

Bulat SA, Doronin MV and Sumbatyan DA (2020) New microbial finds in the Subglacial Antarctic Lake Vostok. Presented at The Eleventh Moscow international Solar System Symposium (11M-S 3), Space Research Institute of RAS, Moscow, Russia, p. 102.

Bulat SA, Ezhov VF and Tselmovich VA (2018b) The first detection of iron-nickel micrometeorites in the snow cover of Central East Antarctica, Vostok station. Presented at the Physicochemical and Petrophysical Research in Earth Sciences. Nineteenth International Conference, IGEM RAS, Moscow, pp. 45–48.

Cheptsov VS (2024) Survival and transfer of microorganisms beyond the Earth: To what extent are microorganisms tolerant to external influences?. *Solar System Research* **58**, S87–S104. https://doi.org/10.1134/S0038094624601087

Cheptsov VS, Belov A, Soloveva O, Vorobyova E, Osipov G, Manucharova N and Gorlenko M (2021a) Survival and growth of soil microbial communities under influence of sodium perchlorates. *International Journal of Astrobiology* **20**, 36–47. https://doi.org/10.1017/S1473550420000312

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Cheptsov VS, Belov A, Vorobyova E, Osipov G and Bulat S (2019) Viability of the soddy–podzolic soil microbial community after 148–1250 kGy gamma irradiation. *Planetary and Space Science* **172**, 8–13. https://doi.org/10.1016/j.pss.2019.04.008

Cheptsov VS, Vorobyova E, Belov A, Pavlov A, Tsurkov D, Lomasov V and Bulat S (2018a) Survivability of soil and permafrost microbial communities after irradiation with accelerated electrons under simulated martian and open space conditions. *Geosciences* **8**, 298. https://doi.org/10.3390/geosciences8080298

Cheptsov VS, Vorobyova EA, Gorlenko MV, Manucharova NA, Pavlov AK and Lomasov VN (2018b) Effect of gamma radiation on viability of a soil microbial community under conditions of Mars. *Paleontological Journal* **52**, 1217–1223. https://doi.org/10.1134/S0031030118100088

Cheptsov VS, Vorobyova EA, Manucharova NA, Gorlenko MV, Pavlov AK, Rozanova MS, Lomasov VN, Belov AA and Chumikov AE (2021b) Prokaryotic community of the ancient Antarctic Permafrost after irradiation with gamma rays under simulated martian conditions. *Eurasian Soil Science* **54**, 417–423. https://doi.org/10.1134/S1064229321030030

Cheptsov VS, Vorobyova EA, Manucharova NA, Gorlenko MV, Pavlov AK, Vdovina MA, Lomasov VN and Bulat SA (2017) 100 kGy gamma-affected microbial communities within the ancient Arctic permafrost under simulated Martian conditions. *Extremophiles* **21**, 1057–1067. https://doi.org/10.1007/s00792-017-0966-7

Cheptsov VS, Vorobyova EA, Osipov GA, Manucharova NA, Polyanskaya LM, Gorlenko MV, Pavlov AK, Rosanova MS and Lomasov VN (2018c) Microbial activity in Martian analog soils after ionizing radiation: Implications for the preservation of subsurface life on Mars. *AIMS Microbiology* **4**, 541–562. https://doi.org/10.3934/microbiol.2018.3.541

Cheptsov VS, Vorobyova EA, Polyanskaya LM, Gorlenko MV, Pavlov AK and Lomasov VN (2018d) Sustainability of extreme microbial ecosystems to the comprehensive impact of physical factors of the martian regolith. *Moscow University Soil Science Bulletin* **73**, 119–123. https://doi.org/10.3103/S0147687418030043

Chernyh NA, Mardanov AV, Gumerov VM, Miroshnichenko ML, Lebedinsky AV, Merkel AY, Crowe D, Pimenov NV, Rusanov II, Ravin NV, Moran MA and Bonch-Osmolovskaya EA (2015) Microbial life in Bourlyashchy, the hottest thermal pool of Uzon Caldera, Kamchatka. *Extremophiles* **19**, 1157–1171. https://doi.org/10.1007/s00792-015-0787-5

Chernyh NA, Merkel AY, Kondrasheva KV, Alimov JE, Klyukina AA, Bonch-Osmolovskaya EA, Slobodkin AI and Davranov KD (2024) At the shores of a vanishing sea: Microbial communities of Aral and Southern Aral sea region. *Microbiology* **93**, 1–13. https://doi.org/10.1134/S0026261723602944

Chetverin AB, Chetverina HV, Demidenko AA and Ugarov VI (1997) Nonhomologous RNA Recombination in a cell-free system: Evidence for a transesterification mechanism guided by secondary structure. *Cell* **88**, 503–513. https://doi.org/10.1016/S0092-8674(00)81890-5

Chetverin AB and Spirin AS (1995) Replicable RNA vectors: Prospects for cell-free gene amplification, expression, and cloning. *Progress in Nucleic Acid Research and Molecular Biology* **51**, 225–270. https://doi.org/10.1016/S0079-6603(08)60880-6

Cockell CS (2020) *Astrobiology: Understanding Life in the Universe*, 2nd Edn. London, United Kingdom: Wiley-Blackwell.

Cockell CS (2024) Astrobiology by Gavriil Tikhov. *Astrobiology* **24**, 643–668. https://doi.org/10.1089/ast.2024.0036

Cook LSJ, Briscoe AG, Fonseca VG, Boenigk J, Woodward G and Bass D (2025) Microbial, holobiont, and tree of life eDNA/eRNA for enhanced ecological assessment. *Trends in Microbiology* **33**, 48–65, https://doi.org/10.1016/j.tim.2024.07.003.

D'Elia T, Veerapaneni R and Rogers SO (2008) Isolation of microbes from Lake Vostok Accretion Ice. *Applied and Environmental Microbiology* **74**, 4962–4965. https://doi.org/10.1128/AEM.02501-07

Deamer D, Damer B and Kompanichenko V (2019) Hydrothermal chemistry and the origin of cellular life. *Astrobiology* **19**, 1523–1537. https://doi.org/10.1089/ast.2018.1979

Deamer D, Singaram S, Rajamani S, Kompanichenko V and Guggenheim S (2006) Self-assembly processes in the prebiotic environment. *Philosophical Transactions of the Royal Society B: Biological Sciences* **361**, 1809–1818. https://doi.org/10.1098/rstb.2006.1905

Demkina E, Mulyukin A, Kozlova A, Zolotareva B and El-Registan G (2015) Response of amylase activity in buried paleosols and subsoil permafrost to low-molecular-weight compounds. *European Journal of Soil Biology* **70**, 31–37. https://doi.org/10.1016/j.ejsobi.2015.07.001

Demkina EV, Soina VS, Registan GIE and Zvyagintsev DG (2000) Reproductive resting forms of Arthrobacter globiformis. *Microbiology* **69**, 309–313. https://doi.org/10.1007/BF02756739

Deshevaya EA, Fialkina SV, Shubralova EV, Tsygankov OS, Khamidullina NM, Vasilyak LM, Pecherkin VY, Shcherbakova VA, Nosovsky AM and Orlov OI (2024) Survival of microorganisms during two-year exposure in outer space near the ISS. *Scientific Reports* **14**, 334. https://doi.org/10.1038/s41598-023-49525-z

Dmitriev VV, Gilichinskii DA, Faizutdinova RN, Shershunov IN, Golubev VI and Duda VI (1997) Detection of viable yeast in 3-million-year-old permafrost soils of Siberia. *Microbiology (in Russian)* **66**, 655–660.

Dvoryanchikova EN, Kizilova AK, Kravchenko IK and Galchenko VF (2011) Analysis of Microbial Communities of Thermal Springs in the Area of the Fumarole Lake of the Uzon Volcano Caldera, Kamchatka. Bulletin of the Samara Scientific Center of the Russian Academy of Sciences (in Russian) 13.

El-Registan GI, Mulyukin AL, Nikolaev YA, Stepanenko IY, Kozlova AN, Martirosova EI, Shanenko EF, Strakhovskaya MG and Revina AA (2005) The role of microbial low-molecular-weight autoregulatory factors (alkylhydroxybenzenes) in resistance of microorganisms to radiation and heat shock. *Advances in Space Research, Space Life Sciences: Aircraft and Space Radiation Environment* **36**, 1718–1728. https://doi.org/10.1016/j.asr.2005.02.070

Evdokimova D, Belyaev D, Montmessin F, Korablev O, Bertaux J-L, Verdier L, Lefèvre F and Marcq E (2021) The spatial and temporal distribution of nighttime ozone and sulfur dioxide in the Venus mesosphere as deduced from SPICAV UV stellar occultations. *Journal of Geophysical Research (Planets)* **126**(3), e06625. https://doi.org/10.1029/2020JE006625

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Fedorova A, Korablev O, Vandaele A-C, Bertaux J-L, Belyaev D, Mahieux A, Neefs E, Wilquet WV, Drummond R, Montmessin F and Villard E (2008) HDO and H_2O vertical distributions and isotopic ratio in the Venus mesosphere by solar occultation at infrared spectrometer on board Venus express. *Journal of Geophysical Research (Planets)* **113**(E12), E00B22. https://doi.org/10.1029/2008JE003146

Finster K, Hansen AA, Liengaard L, Mikkelsen K, Kristoffersen T, Merrison J, Nørnberg P and Lomstein BA (2008) The use of complex microbial soil communities in Mars simulation experiments. *International Journal of Astrobiology* **7**, 169–176. https://doi.org/10.1017/S1473550408004163

Frank YA, Kadnikov VV, Gavrilov SN, Banks D, Gerasimchuk AL, Podosokorskaya OA, Merkel AY, Chernyh NA, Mardanov AV, Ravin NV, Karnachuk OV and Bonch-Osmolovskaya EA (2016) Stable and variable parts of microbial community in siberian deep subsurface thermal aquifer system revealed in a long-term monitoring study. *Frontiers in Microbiology* **7**, 2101. https://doi.org/10.3389/fmicb.2016.02101

Freidzon AY, Valiev RR and Berezhnoy AA (2014) Ab initio simulation of pyrene spectra in water matrices. *RSC Advances* **4**, 42054–42065. https://doi.org/10.1039/C4RA05574H

Frolov A, Didio A, Ihling C, Chantzeva V, Grishina T, Hoehenwarter W, Sinz A, Smolikova G, Bilova T and Medvedev S (2018) The effect of simulated microgravity on the Brassica napus seedling proteome. *Functional Plant Biology* **45**(4), 440–452. https://doi.org/10.1071/FP16378

Frolov EN, Elcheninov AG, Gololobova AV, Toshchakov SV, Novikov AA, Lebedinsky AV and Kublanov IV (2023a) Obligate autotrophy at the thermodynamic limit of life in a new acetogenic bacterium. *Frontiers in Microbiology* **14**, 1185739. https://doi.org/10.3389/fmicb.2023.1185739.

Frolov EN, Gololobova AV, Klyukina AA, Bonch-Osmolovskaya EA, Pimenov NV, Chernyh NA and Merkel AY (2021) Diversity and activity of sulfate-reducing prokaryotes in Kamchatka hot springs. *Microorganisms* **9**, 2072. https://doi.org/10.3390/microorganisms9102072

Frolov EN, Lebedinsky AV, Elcheninov AG and Kublanov IV (2023b) Taxonomic proposal for a deep branching bacterial phylogenetic lineage: Transfer of the family Thermodesulfobiaceae to Thermodesulfobiales ord. nov., Thermodesulfobiia classis nov. and Thermodesulfobiota phyl. nov. *Systematic and Applied Microbiology* **46**(1):126388. https://doi.org/10.1016/j.syapm.2022.126388

Frontasyeva MV, Tselmovich VA and Steinnes E (2018) Atmospheric deposition of cosmic dust studied by moss analysis. 81st Annual Meeting of the Meteoritical Society, 22–27 July, Moscow, Russia, p. 6160.

Gacheva A (2004) Project of the Future: A Version of Russian Cosmism. Lecture: "Space and the future", Feb. 13. N.F. Fedorov Library 180. Moscow.

Galchenko VF (2001) *Methanotrophic Bacteria*. Moscow: GEOS.

Galchenko VF (2002) Microorganisms in hydrothermal communities. In Gebruk AV (ed), *Biology of Hydrothermal Systems*. Moscow: KMK Press, pp. 113–130.

Galimov EM (2001) *Phenomenon of Life. Between Equilibrium and Nonlinearity. Origin and Principles of Evolution*. Moscow: URSS.

Galimov EM (2004) Phenomenon of life: Between equilibrium and non-linearity. *Origins of Life and Evolution of the Biosphere* **34**, 599–613. https://doi.org/10.1023/B:ORIG.0000043131.86328.9d

Galimov EM (2009) Concept of sustained ordering and an ATP-related Mechanism of Life's Origin. *International Journal of Molecular Sciences* **10**, 2019–2030. https://doi.org/10.3390/ijms10052019

Galimov EM (2009) Conditions for the origin of life on Earth. *Biosphere (in Russian)* **1**, 039–047.

Galimov EM, Sevast'yanov VS, Karpov GA, Kamaleeva AI, Kuznetsova OV, Konopleva IV and Vlasova LN (2015) Hydrocarbons from a volcanic area. Oil seeps in the Uzon caldera, Kamchatka. *Geochemistry International* **53**, 1019–1027. https://doi.org/10.1134/S0016702915120046

Gerasimenko LM, Karpov GA, Orleanskiy VK and Zavarzin GA (1983) The role of the cyanobacterial filter in the transformation of gas components of hydrothermal vents on the example of the Uzon caldera in Kamchatka. *Journal of General Biology (in Russian)* **44**, 842–851.

Gerasimov MV (2002) Toxins produced by meteorite impacts and their possible role in a biotic mass extinction. In Koeberl C and MacLeod KG (eds), *Catastrophic Events and Mass Extinctions: Impacts and Beyond*. Boulder, Colorado: Geological Society of America, pp. 705–716.

Gerasimov MV, Mukhin LM and Nussinov MD (1984) Investigation of the chemical composition of the gas phase that is forming by action of a laser pulse on some rocks and minerals. *Reports of the USSR Academy of Sciences (in Russian)* **275**, 646–650.

Gerasimov MV, Mukhin LM and Safonova EN (1991) Formation of organic matter at intense vaporization of meteorites and rocks. *News of the USSR Academy of Sciences, Geological Series (in Russian)* **4**, 119–126.

Gilichinsky D, Rivkina E, Bakermans C, Shcherbakova V, Petrovskaya L, Ozerskaya S, Ivanushkina N, Kochkina G, Laurinavichuis K, Pecheritsina S, Fattakhova R and Tiedje JM (2005) Biodiversity of cryopegs in permafrost. *FEMS Microbiology Ecology* **53**, 117–128. https://doi.org/10.1016/j.femsec.2005.02.003

Gilichinsky D, Rivkina E, Shcherbakova V, Laurinavichuis K and Tiedje J (2003) Supercooled water brines within permafrost-an unknown ecological niche for microorganisms: A model for astrobiology. *Astrobiology* **3**, 331–341. https://doi.org/10.1089/153110703769016424

Gilichinsky D, Vishnivetskaya T, Petrova M, Spirina E, Mamykin V and Rivkina E (2008) Bacteria in permafrost. In Margesin R, Schinner F, Marx J-C and Gerday C (eds), *Psychrophiles: From Biodiversity to Biotechnology*. Berlin, Heidelberg: Springer, pp. 83–102. https://doi.org/10.1007/978-3-540-74335-4_6

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Gilichinsky D and Wagener S (1995) Microbial life in permafrost: A historical review. *Permafrost and Periglacial Processes* **6**, 243–250. https://doi.org/10.1002/ppp.3430060305

Gilichinsky DA (1997) Permafrost as a microbial habitat: extreme for the Earth, favorable in space. In *Instruments, Methods, and Missions for the Investigation of Extraterrestrial Microorganisms. Presented at the Instruments, Methods, and Missions for the Investigation of Extraterrestrial Microorganisms*. SPIE Proceedings, SPIE Optical Science, Engineering and Instrumentation, San Diego, US, 27 July, pp. 472–480. https://doi.org/10.1117/12.278803

Gilichinsky DA (2002) Permafrost model of extraterrestrial habitat. In Horneck G, Baumstark-Khan C (eds), *Astrobiology: The Quest for the Conditions of Life*. Berlin, Heidelberg: Springer, pp. 125–142. https://doi.org/10.1007/978-3-642-59381-9_9

Gilichinsky DA, Khlebnikova GM, Zvyagintsev DG, Fedorov-Davydov DG and Kudryavtseva NN (1989) Microbial characteristics under cryolythozone sedimentary rocks investigations. *Izvestiya Akademii Nauk SSSR, Seriya Geologicheskaya* **6**, 103–115.

Gilichinsky DA, Soina VS and Petrova MA (1993) Cryoprotective properties of water in the Earth cryolithosphere and its role in exobiology. *Origins of Life and Evolution of the Biosphere* **23**, 65–75. https://doi.org/10.1007/BF01581991

Gilichinsky DA, Vorobyova EA, Erokhina LG, Fyordorov-Davydov DG, Chaikovskaya NR, Fyordorov-Dayvdov DG (1992) Long-term preservation of microbial ecosystems in permafrost. *Advances in Space Research* **12**, 255–263. https://doi.org/10.1016/0273-1177(92)90180-6

Gilichinsky DA, Wagener S and Vishnevetskaya TA (1995) Permafrost microbiology. *Permafrost and Periglacial Processes* **6**, 281–291. https://doi.org/10.1002/ppp.3430060402

Gilichinsky DA, Wilson GS, Friedmann EI, McKay CP, Sletten RS, Rivkina EM, Vishnivetskaya TA, Erokhina LG, Ivanushkina NE, Kochkina GA, Shcherbakova VA, Soina VS, Spirina EV, Vorobyova EA, Fyodorov-Davydov DG, Hallet B, Ozerskaya SM, Sorokovikov VA, Laurinavichyus KS, Shatilovich AV, Chanton JP, Ostroumov VE, Tiedje JM (2007) Microbial populations in Antarctic permafrost: Biodiversity, state, age, and implication for astrobiology. *Astrobiology* **7**, 275–311. https://doi.org/10.1089/ast.2006.0012

Gindilis LM and Gurvits LI (2019) SETI in Russia, USSR and the post-Soviet space: A century of research. *Acta Astronautica* **162**, 1–13. https://doi.org/10.1016/j.actaastro.2019.04.030

Goldanskii V and Kuzmin VV (1991) Chirality and cold origin of life. *Nature* **352**, 114–114. https://doi.org/10.1038/352114a0

Goldanskii VI (1977) Interstellar grains as possible cold seeds of life. *Nature* **269**, 583–584. https://doi.org/10.1038/269583a0

Goldanskii VI (1993) Revival of the concept of the cold prehistory of life. *European Review* **1**, 137–147. https://doi.org/10.1017/S106279870000048X

Goldanskii VI (1997) Nontraditional pathways of extraterrestrial formation of prebiotic Matter. *Journal of Physical Chemistry A* **101**, 3424–3432. https://doi.org/10.1021/jp970042i

Gontareva NB, Simakov MB and Kuzicheva EA (2013) Space flight experiments with nonterrestrial minerals and bioorganic molecules. *Paleontological Journal* **47**, 1070–1073. https://doi.org/10.1134/S0031030113090086

Gorlenko VM (2007) Anoxygenic phototrophic bacteria of soda lakes. In *Proceedings of the Winogradsky Institute of Microbiology*, Vol. XIV. Moscow, Nauka: Alkaliphilic Microbial Communities, pp. 225–257.

Grachev AF, Tselmovich VA and Korchagin OA (2008) Cosmic dust and micrometeorites in ancient earth layers. *Earth and Universe (in Russian)* **5**, 59–67.

Grinberg M, Nemtsova Y, Ageyeva M, Brilkina A and Vodeneev V (2023) Effect of low-dose ionizing radiation on spatiotemporal parameters of functional responses induced by electrical signals in tobacco plants. *Photosynthesis Research* **157**(2–3), 119–132. https://doi.org/10.1007/s11120-023-01027-9

Grinberg M and Vodeneev V (2025) The role of signaling systems of plant in responding to key astrophysical factors: Increased ionizing radiation, near-null magnetic field and microgravity. *Planta* **261**(2), 31. https://doi.org/10.1007/s00425-025-04610-7

Grinberg MA, Gudkov SV, Balalaeva IV, Gromova E, Sinitsyna Y, Sukhov V and Vodeneev V (2021) Effect of chronic β-radiation on long-distance electrical signals in wheat and their role in adaptation to heat stress. *Environmental and Experimental Botany* **184**, 104378. https://doi.org/10.1016/j.envexpbot.2021.104378

Grinberg MA, Il'in NV, Nemtsova YA, Dolinin AA, Ivanova AV, Sarafanov FG, Pirogova PA, Volkova AV, A Vodeneev V and Mareev EA (2025) Effect of ionizing radiation and near-null magnetic field on electrical signals of plants. *Radiophysics and Quantum Electronics* **67**, 788–798. https://doi.org/10.1007/s11141-025-10418-y.

Grinspoon DH (1997) *Venus Revealed: A New Look below the Clouds of Our Mysteriious Twin Planet*. West Newton, US: Basic Books.

Gudkov SV, Grinberg MA, Sukhov V and Vodeneev V (2019) Effect of ionizing radiation on physiological and molecular processes in plants. *Journal of Environmental Radioactivity* **202**, 8–24. https://doi.org/10.1016/j.jenvrad.2019.02.001

Gusev VA (2002) Chemical evolution in a thunderstorm cloud. *Doklady Chemistry* **385**, 186–188. https://doi.org/10.1023/A:1016583017174

Guzik P and Drahus M (2021) Gaseous atomic nickel in the coma of interstellar comet 2I/Borisov. *Nature* **593**, 375–378. https://doi.org/10.1038/s41586-021-03485-4

Heizer A and Nascimento-Dias B (2023) A philosophical and historical perspective about terms Astrobiology, Exobiology, Cosmobiology, Xenology and Bioastronomy. *Revista Opinião Filosófica* **14**, 1–16. https://doi.org/10.36592/opiniaofilosofica.v14.1094

Hill ML (2023) A catalog of habitable zone exoplanets. *The Astronomical Journal* **165**, 34 (16pp). https://doi.org/10.48550/arXiv.2210.02484

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Hoover RB, Rozanov AY, Krasavin EA, Ryumin AK and Kapralov MI (2018) Diatoms in the orgueil meteorite. *Paleontological Journal* **52**, 1647–1650. https://doi.org/10.1134/S0031030118130051

Horneck G, Walter N, Westall F, Grenfell JL, Martin WF, Gomez F, Leuko S, Lee N, Onofri S, Tsiganis K, Saladino R, Pilat-Lohinger E, Palomba E, Harrison J, Rull F, Muller C, Strazzulla G, Brucato JR, Rettberg P and Capria MT (2016) AstRoMap European Astrobiology Roadmap. *Astrobiology* **16**(3), 201–243. https://doi.org/10.1089/ast.2015.1441.

Imshenetsky AA, Abyzov SS, Voronov GT, Zhukova AI and Lysenko SV (1966) The possibility of life in outer space. *Life Sciences in Space Research* **4**, 121–130.

Imshenetsky AA and Lysenko SV (1965) Ultra-high vacuum and microorganisms. *Life Sciences in Space Research* **3**, 142–148.

Imshenetsky AA, Lysenko SV and Kazakov GA (1978) Upper boundary of the biosphere. *Applied and Environmental Microbiology* **35**, 1–5. https://doi.org/10.1128/aem.35.1.1-5.1978

Isachenko BL (1912) Some data on permafrost bacteria. *News of the St. Petersburg Botanical Garden (in Russian)* **12**(5–6), 140.

Ivlev A, Akimkin V, Silsbee K and Wiebe D (2024) Chapter 9 - Microphysics of cosmic dust. In Bovino S and Grassi T (eds), *Astrochemical Modeling*. Cambridge, US: Elsevier, pp. 235–282. https://doi.org/10.1016/B978-0-32-391746-9.00018-3

Kalinichenko VI, Bondarev VB, Gerasimov MV, Mukhin LM and Safonova EN (1977) Synthesis of organic compounds under conditions simulating the Jovian atmosphere. *Reports of the USSR Academy of Sciences (in Russian)* **236**, 245–248.

Karaseva AI, Elcheninov AG, Prokofeva MI, Klyukina AA and Kochetkova TV (2024) Microbial diversity of hot springs of the Kuril Islands. *BMC Microbiology* **24**, 547. https://doi.org/10.1186/s12866-024-03704-8

Kardashev NS (1964) Transmission of information by extraterrestrial civilizations. *Astronomical Journal (in Russian)* **41**, 217–221.

Kardashev NS (1978) On strategy in the search for extraterrestrial civilizations. *Soviet Studies in Philosophy (in Russian)* **17**(1), 33–53. https://doi.org/10.2753/RSP1061-1967170133

Karnachuk OV, Frank YA, Lukina AP, Kadnikov VV, Beletsky AV, Mardanov AV and Ravin NV (2019) Domestication of previously uncultivated Candidatus Desulforudis audaxviator from a deep aquifer in Siberia sheds light on its physiology and evolution. *The ISME Journal* **13**(8), 1947–1959. https://doi.org/10.1038/s41396-019-0402-3

Kasatkina AN, Abramov AA and Belov AA (2025) Microbiological characteristics of cultivated prokaryotic communities of fumarole fields in the permafrost zone. *Eurasian Soil Science* **8**, 1069–1082. https://doi.org/10.31857/S0032180X25080065

Kim YJ, Lee HS, Kim ES, Bae SS, Lim JK, Matsumi R, Lebedinsky AV, Sokolova TG, Kozhevnikova DA, Cha SS, Kim SJ, Kwon KK, Imanaka T, Atomi H, Bonch-Osmolovskaya EA, Lee JH and Kang SG (2010) Formate-driven growth coupled with H_2 production. *Nature* **467**(7313), 352–5. https://doi.org/10.1038/nature09375.

Kirsanova MS, Baklanov PV, Vasiliev EO, Vasyunin AI, Wiebe DS, Drozdov SA, Larchenkova TI, Likhachev SF, Moiseev AV, Pavlyuchenkov YAN, Sozinova PS, Topchieva AP, Tret'yakov IV, Fedoseev GS, Khudchenko AV and Shakhvorostova NN (2025) The origin and transport of water in the universe. *Advances in Physical Sciences (in Russian)* **195**(3), 294–310. https://doi.org/10.3367/UFNe.2024.08.039744

Kissel J, Sagdeev RZ, Bertaux JL, Angarov VN, Audouze J, Blamont JE, Büchler K, Evlanov EN, Fechtig H, Fomenkova MN, von Hoerner H, Inogamov NA, Khromov VN, Knabe W, Krueger FR, Langevin Y, Leonas VB, Levasseur-Regourd AC, Managadze GG, Podkolzin SN, Shapiro VD, Tabaldyev SR and Zubkov BV (1986) Composition of comet Halley dust particles from vega observations. *Nature* **321**, 280–282. https://doi.org/10.1038/321280a0

Kochetkova TV, Podosokorskaya OA, Elcheninov AG and Kublanov IV (2022) Diversity of thermophilic prokaryotes inhabiting Russian natural hot springs. *Microbiology* **91**, 3–31. https://doi.org/10.1134/S0026261722010064

Kochina O and Wiebe D (2014) Organic compounds in star forming regions. *Origins of Life and Evolution of the Biosphere* **44**, 169–174. https://doi.org/10.1007/s11084-014-9378-1

Kochina OV and Wiebe DS (2015) The possibility of diagnosing evolutionary stages of a protostellar object using observations of complex molecules. *Astronomy Reports* **59**, 762–771. https://doi.org/10.1134/S1063772915080041

Kochina OV and Wiebe DS (2020) Deuterated isotopologues of water and methanol in star-forming regions. *Astronomy Letters* **46**, 379–387. https://doi.org/10.1134/S1063773720060055

Kochkina GA, Ivanushkina NE, Karasev SG, Gavrish EY, Gurina LV, Evtushenko LI, Spirina EV, Vorob'eva EA, Gilichinskii DA and Ozerskaya SM (2001). Survival of micromycetes and actinobacteria under conditions of long-term natural cryopreservation. *Microbiology* **70**, 356–364. https://doi.org/10.1023/A:1010419831245

Kolb VM (2019) *Handbook of Astrobiology.* Boca Raton, US: CRC Press.

Kolesnikov MP, Telegina TA, Lyudnikova TA and Kritsky MS (2008) Abiogenic photophosphorylation of ADP to ATP sensitized by flavoproteinoid microspheres. *Origins of Life and Evolution of the Biosphere* **38**, 243–255. https://doi.org/10.1007/s11084-008-9130-9

Kompanichenko V (2019) The rise of a habitable planet: Four required conditions for the origin of life in the universe. *Geosciences* **9**, 92. https://doi.org/10.3390/geosciences9020092

Kompanichenko VN (2017) Thermodynamic Inversion. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-53512-8

Kompanichenko VN (2023). Abiotic-to-biotic transition of organic systems starting with thermodynamic inversion. In Kolb V and Clark B (eds), *Guidebook for Systems Applications in Astrobiology.* Boca Raton, US: CRC Press, pp. 164–176.

Kompanichenko VN, Poturay VA and Karpov GA (2016) Organic compounds in thermal water: The Mutnovskii area and the Uzon caldera. *Journal of Volcanology and Seismology.* **10**, 305–319. https://doi.org/10.1134/S0742046316050031

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Kompanichenko VN, Poturay VA and Rapoport VL (2010) Organic matter in hydrothermal systems on the Russian far East in the context of prebiotic chemistry. *Origins of Life and Evolution of the Biosphere* **40**, 516–517. https://doi.org/10.1007/s11084-010-9215-0

Kondrasheva KV, Umruzokov AA, Kalenov SV, Merkel AY, Chernyh NA, Slobodkin AI, Gavrilov SN and Davranov KD (2023) Calcinating bacteria in extreme ecosystems of the Southern Aral Region. Microbiology 92, 473–480. https://doi.org/10.1134/S0026261723600325

Konyukhov IV, Pogosyan SI, Garipov GK and Rubin AB (2023) Using fluorimetric methods to search for extraterrestrial photosynthetic organisms. Presented at the The fourteenth Moscow Solar System Symposium, Space Research Institute of RAS, Moscow, Russia, pp. 371–372.

Koonin EV (2007) The cosmological model of eternal inflation and the transition from chance to biological evolution in the history of life. *Biology Direct* **2**, 15. https://doi.org/10.1186/1745-6150-2-15

Koonin EV (2011) *The Logic of Chance: The Nature and Origin of Biological Evolution*. New Jersey, US: FT Press.

Korablev O, Vandaele AC, Montmessin F, Fedorova AA, Trokhimovskiy A, Forget F, Lefèvre F, Daerden F, Thomas IR, Trompet L, Erwin JT, Aoki S, Robert S, Neary L, Viscardy S, Grigoriev AV, Ignatiev NI, Shakun A, Patrakeev A, Belyaev DA, Bertaux J-L, Olsen KS, Baggio L, Alday J, Ivanov YS, Ristic B, Mason J, Willame Y, Depiesse C, Hetey L, Berkenbosch S, Clairquin R, Queirolo C, Beeckman B, Neefs E, Patel MR, Bellucci G, López-Moreno J-J, Wilson CF, Etiope G, Zelenyi L, Svedhem H, Vago JL, Science Team ACS, and Science Team NOMAD (2019) No detection of methane on Mars from early ExoMars trace gas orbiter observations *Nature* **568**(7753), 517–520. https://doi.org/10.1038/s41586-019-1096-4

Kotsyurbenko O, Duplex O, Roey A, Golyshina O, Golyshin P and Vorobyova E (2012) Chemolithotrophic microorganisms and microbial community from the desert soil as candidates for the phobos-grunt space return mission. *Paleontological Journal* **46**, 1075–1076.

Kotsyurbenko OR, Cordova JA, Belov AA, Cheptsov VS, Kölbl D, Khrunyk YY, Kryuchkova MO, Milojevic T, Mogul R, Sasaki S, Słowik G.P, Snytnikov V and Vorobyova EA (2021) Exobiology of the Venusian clouds: New insights into habitability through terrestrial models and methods of detection. *Astrobiology* **21**, 1186–1205. https://doi.org/10.1089/ast.2020.2296

Kotsyurbenko OR and Govorova AF (2024) Philosophy of cosmism and the formation of Russian astrobiology. *Zemlya I Vselennaya* **3**, 49–74. (in Russian).

Kotsyurbenko OR, Kompanichenko VN, Brouchkov AV, Khrunyk YY, Karlov SP, Sorokin VV and Skladnev DA (2024) Different scenarios for the origin and the subsequent succession of a hypothetical microbial community in the Cloud Layer of Venus. *Astrobiology* **24**, 423–441. https://doi.org/10.1089/ast.2022.0117

Kotsyurbenko OR, Skladnev DA and Jheeta S (2023) Systems approach to microbial communities and its application to astrobiology. In Kolb VM (ed), *Guidebook for Systems Applications in Astrobiology*. Boca Raton, US: CRC Press, pp. 186–209. https://doi.org/10.1201/9781003294276-10

Kozlov SV, Terashkevich VA, Pazyuk EA, Stolyarov AV, Yurchenko SN and Tennyson J (2024) An upgraded line list for radiative transitions between the B2Σ+, A2Π, and X2Σ+ states of the CN radical. *Astrophysical Journal, Supplement Series* **275**(2), 29. https://doi.org/10.3847/1538-4365/ad8b40

Krasnopolsky VA, Maillard JP and Owen TC (2004) Detection of methane in the martian atmosphere: Evidence for life?. *Icarus* **172**(2), 537–547. https://doi.org/10.1016/j.icarus.2004.07.004

Kritsky MS (1996) Coenzyme photoreceptors as a field for studies of the evolutionary continuity of metabolic systems. *Origins of Life and Evolution of the Biosphere* **26**, 470–471. https://doi.org/10.1007/BF02459875

Kritsky MS, Kolesnikov MP and Telegina TA (2007) Modeling of abiogenic synthesis of ATP. *Dokl Biochem Biophys* **417**, 313–315. https://doi.org/10.1134/S1607672907060063

Kritsky MS, Lyudnikova TA, Mironov EA and Neverov KV (1998) The evolutionary aspects of coenzyme photobiochemistry. In Chela-Flores J and Raulin F (eds), *Exobiology: Matter, Energy, and Information in the Origin and Evolution of Life in the Universe*. Dordrecht: Springer Netherlands, pp. 187–190. https://doi.org/10.1007/978-94-011-5056-9_24

Kritsky MS, Telegina TA, Lyudnikova TA and Zemskova YL (2004) Coenzymes in evolution of the RNA world. In Seckbach J, Chela-Flores J, Owen T and Raulin F (eds), *Life in the Universe: From the Miller Experiment to the Search for Life on Other Worlds*. Dordrecht: Springer Netherlands, pp. 115–118. https://doi.org/10.1007/978-94-007-1003-0_19

Kritsky MS, Telegina TA, Vechtomova YL, Kolesnikov MP, Lyudnikova TA and Buglak AA (2013) Photoexcited molecules of pteridine derivatives in prebiotic and biological evolution. *Paleontological Journal* **47**, 1074–1079. https://doi.org/10.1134/S0031030113090104

Kryazhevskikh NA, Demkina EV, Loiko NG, Baslerov RV, Kolganova TV, Soina VS, Manucharova NA, Gal'chenko VF and El'-Registan GI (2013) Comparison of the adaptive potential of the Arthrobacter oxydans and Acinetobacter lwoffii isolates from permafrost sedimentary rock and the analogous collection strains. *Microbiology* **82**, 29–42. https://doi.org/10.1134/S0026261713010050

Kublanov IV, Perevalova AA, Slobodkina GB, Lebedinsky AV, Bidzhieva SK, Kolganova TV, Kaliberda EN, Rumsh LD, Haertlé T and Bonch-Osmolovskaya EA (2009) Biodiversity of thermophilic prokaryotes with hydrolytic activities in hot springs of Uzon Caldera, Kamchatka (Russia). *Applied and Environmental Microbiology* **75**, 286–291. https://doi.org/10.1128/AEM.00607-08

Kublanov IV, Sigalova OM, Gavrilov SN, Lebedinsky AV, Rinke C, Kovaleva O, Chernyh NA, Ivanova N, Daum C, Reddy TB, Klenk HP, Spring S, Göker M, Reva ON, Miroshnichenko ML, Kyrpides NC, Woyke T, Gelfand MS and Bonch-Osmolovskaya EA (2017) Genomic analysis of Caldithrix abyssi, the thermophilic anaerobic bacterium of the novel bacterial phylum calditrichaeota. *Frontiers in Microbiology* **8**, 195. https://doi.org/10.3389/fmicb.2017.00195.

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Kuzicheva EA and Gontareva NB (2003) Exobiological investigations on Russian spacecrafts. *Astrobiology* **3**(2), 253–261, https://doi.org/10.1089/153110703769016352

Lammer H, Sproß L, Grenfell JL, Scherf M, Fossati L, Lendl M and Cubillos PE (2019) The role of N_2 as a geo-biosignature for the detection and characterization of Earth-like habitats. *Astrobiology* **19**, 927–950. https://doi.org/10.1089/ast.2018.1914

Lavire C, Normand P, Alekhina I, Bulat S, Prieur D, Birrien J-L, Fournier P, Hänni C and Petit J-R (2006) Presence of hydrogenophilus thermoluteolus DNA in accretion ice in the subglacial Lake Vostok, Antarctica, assessed using rrs, cbb and hox. *Environmental Microbiology* **8**, 2106–2114. https://doi.org/10.1111/j.1462-2920.2006.01087.x

Lavrentyeva E, Banzaraktsaeva T, Dambaev V, Buyantueva L, Valova E, Ivanov V and Plotnikov A (2023) Taxonomic diversity and functional potential of microbial communities in salt lakes Gudzhirganskoe and Nukhe-Nur (Barguzin depression, Baikal Rift Zone). *Biological Communications* **68**(2), 86–96. https://doi.org/10.21638/spbu03.2023.203

Lebedeva EG and Kharitonova NA (2020) Ecological and biochemical properties of thermophilic bacteria isolated from the Dachnye hot springs of Kamchatka (Far East, Russia). *Samara Scientific Bulletin (in Russian)* **9**, 79–85. https://doi.org/10.17816/snv202093114

Lefèvre F, Trokhimovskiy A, Fedorova A, Baggio L, Lacombe G, Määttänen A, Bertaux J.-L, Forget F, Millour E, Venot O, Bénilan Y, Korablev O and Montmessin F (2021) Relationship between the ozone and water vapor columns on Mars as observed by SPICAM and calculated by a global climate model. *Journal of Geophysical Research (Planets)* **126**(4), e06838. https://doi.org/10.1029/2021JE006838

Levinskikh MA, Sychev VN, Derendyaeva TA, Signalova OB, Salisbury FB, Campbell WF, Bingham GE, Bubenheim DL and Jahns G (2000) Analysis of the spaceflight effects on growth and development of Super Dwarf wheat grown on the Space Station Mir. *Journal of Plant Physiology* **156**(4), 522–529. https://doi.org/10.1016/s0176-1617(00)80168-6.

Limaye SS, Mogul R, Smith DJ, Ansari AH, Słowik GP and Vaishampayan P (2018) Venus' spectral signatures and the potential for life in the clouds. *Astrobiology* **18**, 1181–1198. https://doi.org/10.1089/ast.2017.1783

Lipenkov V and Istomin V (2001) On the stability of air clathrate-hydrate crystals in subglacial Lake Vostok. *Antarctica* **91**, 138–149.

Lipenkov VY, Ekaykin AA, Polyakova EV and Raynaud D (2016) Characterization of subglacial Lake Vostok as seen from physical and isotope properties of accreted ice. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* **374**, 20140303. https://doi.org/10.1098/rsta.2014.0303

Litvak ML, Sanin AB, Mitrofanov IG, Bakhtin B, Jun I, Martinez-Sierra LM, Nosov AV and Perkhov AS (2020) Mars neutron radiation environment from HEND/Odyssey and DAN/MSL observations. *Planetary and Space Science* **184**, 104866. https://doi.org/10.1016/j.pss.2020.104866

Livingstone SJ, Li Y, Rutishauser A, Sanderson RJ, Winter K, Mikucki JA, Björnsson H, Bowling JS, Chu W, Dow CF, Fricker HA, McMillan M, Ng FSL, Ross N, Siegert MJ, Siegfried M and Sole A.J (2022) Subglacial lakes and their changing role in a warming climate. *Nature Reviews Earth & Environment* **3**(2), 106–124. https://doi.org/10.1038/s43017-021-00246-9.

Lohrmann R and Orgel L (1968) Prebiotic synthesis: Phosphorylation in aqueous solution. *Science* **161**(3836), 64–66. American Association for the Advancement of Science.

Luginin M, Fedorova A, Belyaev D, Montmessin F, Korablev O and Bertaux J-L (2024) Bimodal aerosol distribution in Venus' upper haze from joint SPICAV-UV and -IR observations on Venus Express *Icarus* **409**, 115866. https://doi.org/10.1016/j.icarus.2023.115866

Määttänen A, Fedorova A, Giuranna M, Hernández-Bernal J, Leseigneur Y, Montmessin F, Olsen KS, Sánchez-Lavega A, Stcherbinine A, Szantai A, Tirsch D, Vincendon M, Willame Y and Wolkenberg P (2024) Dust and clouds on Mars: The view from Mars express *Space Science Reviews* **220**(6), 63. https://doi.org/10.1007/s11214-024-01092-z

Malakhov AV, Mitrofanov IG, Golovin DV, Litvak ML, Sanin AB, Djachkova MV and Lukyanov NV (2022) High resolution map of water in the Martian regolith observed by FREND neutron telescope onboard ExoMars TGO. *Journal of Geophysical Research (Planets)* **127**(5), e07258. https://doi.org/10.1029/2022JE007258

Malaterre C and Lareau F (2023) The emergence of astrobiology: A topic-modeling perspective. *Astrobiology* **23**, 496–512. https://doi.org/10.1089/ast.2022.0122

Malavin S, Shmakova L, Claverie J-M and Rivkina E (2020) Frozen zoo: A collection of permafrost samples containing viable protists and their viruses. *Biodiversity Data Journal* **8**, e51586. https://doi.org/10.3897/BDJ.8.e51586

Malli Mohan GB, Parker CW, Urbaniak C, Singh NK, Hood A, Minich JJ, Knight R, Rucker M and Venkateswaran K (2020) Microbiome and metagenome analyses of a closed habitat during human occupation. *mSystems* **5**, e00367–20. https://doi.org/10.1128/mSystems.00367-20.

Managadze G (2007) A new universal mechanism of organic compounds synthesis during prebiotic evolution. *Planetary and Space Science* **55**, 134–140. https://doi.org/10.1016/j.pss.2006.05.024

Managadze G, 2010. Plasma and collision processes of hypervelocity meteorite impact in the prehistory of life. *International Journal of Astrobiology* **9**, 157–174. https://doi.org/10.1017/S147355041000008X

Managadze GG (2009) *Meteorite Impact Plasma and Prebiological Evolution*. Moscow: Fizmatlit.

Managadze GG, Brinckerhoff WB and Chumikov AE (2003) Possible synthesis of organic molecularions in plasmas similar to those generated in hypervelocity impacts. *International Journal of Impact Engineering, Hypervelocity Impact* **29**, 449–458. https://doi.org/10.1016/j.ijimpeng.2003.09.041

Managadze GG, Engel MH, Getty S, Wurz P, Brinckerhoff WB, Shokolov AG, Sholin GV, Terent'ev SA, Chumikov AE, Skalkin AS, Blank VD, Prokhorov VM, Managadze NG and Luchnikov KA (2016) Excess of l-alanine in amino acids synthesized in a

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

plasma torch generated by a hypervelocity meteorite impact reproduced in the laboratory. *Planetary and Space Science* **131**, 70–78. https://doi.org/10.1016/j.pss.2016.07.005

Managadze GG, Safronova AA, Luchnikov KA, Vorobyova EA, Duxbury NS, Wurz P, Managadze NG, Chumikov AE and Khamizov RK (2017) A new method and mass-spectrometric instrument for extraterrestrial microbial life detection using the elemental composition analyses of Martian regolith and permafrost/ice. *Astrobiology* **17**(5), 448–458. https://doi.org/10.1089/ast.2016.1511

Markov A (2015) In search of the beginning of evolution. *Priroda* **1**, 3–13.

Marov M (2024) Soviet/Russian planetary exploration: Historical highlights. *Journal of Physics: Conference Series* **2877**, 012048. https://doi.org/10.1088/1742-6596/2877/1/012048

Marov MY (2013) Vladimir Ivanovich Vernadsky: Studies of the biosphere and astrobiology. *Noosfera (in Russian)* **3**, 111–131.

Marov MY (2023) Astronomical and cosmochemical aspects of the life origin problem. *Astronomy Reports* **67**, 764–789. https://doi.org/10.1134/S1063772923080073

Marov MY and Ipatov SI (2005) Migration of dust particles and delivery of volatiles to the terrestrial planets. *Solar System Research* **39**, 374–380. https://doi.org/10.1007/s11208-005-0050-1

Marov MY (2015) Astrobiology: Basic concepts. In Marov MY (ed), *The Fundamentals of Modern Astrophysics: A Survey of the Cosmos from the Home Planet to Space Frontiers*. New York, NY: Springer, pp. 259–277. https://doi.org/10.1007/978-1-4614-8730-2_9

Martinez Sierra LM, Jun I, Ehresmann B, Zeitlin C, Guo J, Litvak M, Harshman K, Hassler D, Mitrofanov IG, Matthiä D and Loffler S (2023) Unfolding the neutron flux spectrum on the surface of Mars using the MSL-RAD and Odyssey-HEND Data. *Space Weather* **21**(8), e2022SW003344. https://doi.org/10.1029/2022SW003344

Matveev VV (2017) Comparison of fundamental physical properties of the model cells (protocells) and the living cells reveals the need in protophysiology. *International Journal of Astrobiology* **16**, 97–104. https://doi.org/10.1017/S1473550415000476

Matveev VV (2019) Cell theory, intrinsically disordered proteins, and the physics of the origin of life. *Progress in Biophysics and Molecular Biology* **149**, 114–130. https://doi.org/10.1016/j.pbiomolbio.2019.04.001

McKay CP, Hand KP, Doran PT, Andersen DT and Priscu JC (2003) Clathrate formation and the fate of noble and biologically useful gases in Lake Vostok, Antarctica. *Geophysical Research Letters* **30**(13), 1702. https://doi.org/10.1029/2003GL017490

Merkel AY, Pimenov NV, Rusanov II, Slobodkin AI, Slobodkina GB, Tarnovetckii IY, Frolov EN, Dubin AV, Perevalova AA and Bonch-Osmolovskaya EA (2017) Microbial diversity and autotrophic activity in Kamchatka hot springs. *Extremophiles* **21**, 307–317. https://doi.org/10.1007/s00792-016-0903-1

Merkel AY, Podosokorskaya OA, Sokolova TG and Bonch-Osmolovskaya EA (2016) Diversity of methanogenic archaea in a terrestrial hot spring 2012 (Valley of Geysers, Kamchatka). *Microbiology* **85**, 327–336.

Miller SL (1953) A production of amino acids under possible primitive earth conditions. *Science* **117**(3046), 528–529. https://doi.org/10.1126/science.117.3046.528.

Mironov VA, Shcherbakova VA, Rivkina EM and Gilichinsky DA (2013) Thermophilic bacteria of the genus Geobacillus from permafrost volcanic sedimentary rocks. *Microbiology* **82**, 389–392. https://doi.org/10.1134/S0026261713030089

Mitev GB, Taylor S, Tennyson J, Yurchenko SN, Buchachenko AA and Stolyarov AV (2022) ExoMol molecular line lists – XLIII. Rovibronic transitions corresponding to the close-lying X2Π and A2Σ+ states of NaO, *Monthly Notices of the Royal Astronomical Society* **511**(2), 2349–2355. https://doi.org/10.1093/mnras/stab3357

Mitrofanov IG (2024) Origin of life on Earth and the Space project Luna-28. *Solar System Research* **58**, S72–S74. https://doi.org/10.1134/S0038094624601117

Mitrofanov IG, Litvak ML, Kozyrev AS, Sanin AB, Tret'yakov VI, Grin'kov VY, Boynton WV, Shinohara C, Hamara D and Saunders RS (2004) Soil water content on Mars as estimated from Neutron measurements by the HEND instrument onboard the 2001 Mars Odyssey Spacecraft. *Solar System Research* **38**(4), 253–257. https://doi.org/10.1023/B:SOLS.0000037461.70809.45

Mitrofanov IG, Nikiforov SY, Djachkova MV, Lisov DI, Litvak ML, Sanin AB and Vasavada AR (2022) Water and chlorine in the martian subsurface along the traverse of NASA's curiosity rover: 1. DAN Measurement profiles along the traverse. *Journal of Geophysical Research (Planets)* **127**(11), e2022JE007327. https://doi.org/10.1029/2022JE007327

Montmessin F, Fedorova A, Alday J, Aoki S, Chaffin M, Chaufray J-Y, Encrenaz T, Fouchet T, Knutsen EW, Korablev O, Liuzzi G, Mayyasi MA, Pankine A, Trokhimovskiy A and Villanueva GL (2024) Mars' water cycle and escape: A view from Mars express and beyond. *Space Science Reviews* **220**(7), 77. https://doi.org/10.1007/s11214-024-01099-6

Montmessin F, Korablev OI, Trokhimovskiy A, Lefèvre F, Fedorova AA, Baggio L, Irbah A, Lacombe G, Olsen KS, Braude AS, Belyaev DA, Alday J, Forget F, Daerden F, Pla-Garcia J, Rafkin S, Wilson CF, Patrakeev A, Shakun A and Bertaux JL (2021) A stringent upper limit of 20 pptv for methane on Mars and constraints on its dispersion outside Gale crater *Astronomy and Astrophysics* **650**, A140. https://doi.org/10.1051/0004-6361/202140389

Mukhin L, Dolnikov G, Evlanov E, Fomenkova M, Prilutsky O and Sagdeev R (1991) Re-evaluation of the chemistry of dust grains in the coma of comet Halley. *Nature* **350**, 480–481. https://doi.org/10.1038/350480a0

Mukhin LM, Gerasimov MV and Safonova EN (1989) Origin of precursors of organic molecules during evaporation of meteorites and mafic terrestrial rocks. *Nature* **340**, 46–48. https://doi.org/10.1038/340046a0

Mulkidjanian AY (2009) On the origin of life in the Zinc world: 1. Photosynthesizing, porous edifices built of hydrothermally precipitated zinc sulfide as cradles of life on Earth. *Biology Direct* **4**, 26. https://doi.org/10.1186/1745-6150-4-26

Mulkidjanian AY, Bychkov AY, Dibrova DV, Galperin MY and Koonin EV (2012) Origin of first cells at terrestrial, anoxic geothermal fields. *Proceedings of the National Academy of Sciences of the United States of America* **109**(14), E821–E830. https://doi.org/10.1073/pnas.1117774109.

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Mulkidjanian AY, Dibrova DV and Bychkov AY (2025) Origin of the RNA World in cold hadean geothermal fields enriched in zinc and potassium: Abiogenesis as a positive fallout from the moon-forming impact?. *Life* **15**(3), 399; https://doi.org/10.3390/life15030399

Mulkidjanian AY and Galperin MY (2007) Physico-chemical and evolutionary constraints for the formation and selection of first biopolymers: Towards the consensus paradigm of the abiogenic origin of life. *Chemistry & Biodiversity* **4**, 2003–2015. https://doi.org/10.1002/cbdv.200790167

Mulkidjanian AY and Galperin MY (2009) On the origin of life in the Zinc world. 2. Validation of the hypothesis on the photosynthesizing zinc sulfide edifices as cradles of life on Earth. *Biology Direct* **4**, 27. https://doi.org/10.1186/1745-6150-4-27

Muller C, Moreau D, Fonteyn D, Bertaux JL and Korablev O (2001) SPICAM-light on Mars-express as a monitor of surface UV radiation and atmospheric oxidants. *Planetary and Space Science* **49**(2), 165–171. https://doi.org/10.1016/S0032-0633(00)00131-8

Mulyukin AL, Demkina EV, Kryazhevskikh NA, Suzina NE, Vorob'eva LI, Duda VI, Galchenko VF and El-Registan GI (2009) Dormant forms of Micrococcus luteus and Arthrobacter globiformis not platable on standard media. *Microbiology* **78**, 407–418. https://doi.org/10.1134/S0026261709040031

Mulyukin AL, Sorokin VV, Vorob'eva EA, Suzina NE, Duda VI, Gal'chenko VF and El'-Registan GI (2002) Detection of microorganisms in the environment and the preliminary appraisal of their physiological state by X-ray microanalysis. *Microbiology* **71**, 723–734. https://doi.org/10.1023/A:1021444309796

Mulyukin AL, Suzina NE, Mel'nikov VG, Gal'chenko VF and El'-Registan GI (2014) Dormant state and phenotypic variability of Staphylococcus aureus and Corynebacterium pseudodiphtheriticum. *Microbiology* **83**, 149–159. https://doi.org/10.1134/S0026261713060088

Mumma MJ, Villanueva GL, Novak RE, Hewagama T, Bonev BP, DiSanti MA, Mandell AM and Smith MD (2009) Strong release of methane on Mars in Northern Summer 2003. *Science* **323**(5917), 1041. https://doi.org/10.1126/science.1165243

Munishkin AV, Voronin LA, Ugarov VI, Bondareva LA, Chetverina HV and Chetverin AB (1991) Efficient templates for Qβ replicase are formed by recombination from heterologous sequences. *Journal of Molecular Biology* **221**, 463–472. https://doi.org/10.1016/0022-2836(91)80067-5

Murga MS, Akimkin VV and Wiebe DS (2022) Efficiency of the top-down polycyclic aromatic hydrocarbon-to-fullerene conversion in ultraviolet irradiated environments. *Monthly Notices of the Royal Astronomical Society* **517**, 3732–3748. https://doi.org/10.1093/mnras/stac2926

Murga MS, Varakin VN, Stolyarov AV and Wiebe DS (2019) The photolysis of aromatic hydrocarbons adsorbed on the surfaces of cosmic dust grains. *Astronomy Reports* **63**(8), 633–641. https://doi.org/10.1134/S1063772919080043

Murga MS, Wiebe DS, Vasyunin AI, Varakin VN and Stolyarov AV (2020) Experimental and theoretical studies of photoinduced reactions in the solid phase of the interstellar medium. *Russian Chemical Reviews* **89**, 430. https://doi.org/10.1070/RCR4912

Nakibov R, Karteyeva V, Petrashkevich I, Ozhiganov M, Medvedev M and Vasyunin A (2025) Solid and Gaseous Methane in IRAS 23385+ 6053 as seen with open JWST data. *The Astrophysical Journal Letters* **978**(2), L46. https://doi.org/10.3847/2041-8213/ada290

Namsaraev BB (ed.) (2009) *Saltish and Salt Lakes of Zabaikalie: Hydrochemistry, Biology*. Ulan-Ude: Buryat State University Publishing Department, p. 340 (page 73).

Namsaraev BB, Gorlenko VM, Namsaraev ZB, Barkhutova DD, Kozyreva LP, Dagurova OP and Tatarinov AV (2008) Evolutionary aspects of geochemical activity of microbial mats in lakes and hydrotherms of baikal rift zone. In Dobretsov N, Kolchanov N, Rozanov A and Zavarzin G (eds), *Biosphere Origin and Evolution*. Boston, MA: Springer US, pp. 189–201. https://doi.org/10.1007/978-0-387-68656-1_13

Namsaraev BB and Namsaraev ZB (2007) Microbial processes of carbon cycles in alkaline lakes of Transbaikalian region and Mongolia. *Proceedings of the Winogradsky Institute of Microbiology, Alkalophilic microbial communities* **XIV**, 299–322.

Namsaraev ZB, Kolganova TV, Patutina EO, Tsyrenova DD and Samylina OS (2018) Cyanobacterial diversity in the Alkaline Lake Khilganta during the dry and wet periods. *Microbiology* **87**, 583–590. https://doi.org/10.1134/S0026261718040136

Namsaraev ZB, Zaitseva SV, Gorlenko VM, Kozyreva LP and Namsaraev BB (2015) Microbial processes and factors controlling their activities in alkaline lakes of the Mongolian plateau. *Chinese Journal of Oceanology and Limnology* **33**, 1391–1401. https://doi.org/10.1007/s00343-015-4373-6

Nascimento-Dias BLdo and Martinez-Frias J (2023) Brief review about history of astrobiology. *International Journal of Astrobiology* **22**, 67–78. https://doi.org/10.1017/S1473550422000386

Nicholson WL, Krivushin K, Gilichinsky D and Schuerger AC (2013) Growth of Carnobacterium spp. from permafrost under low pressure, temperature, and anoxic atmosphere has implications for Earth microbes on Mars. *Proceedings of the National Academy of Sciences* **110**, 666–671. https://doi.org/10.1073/pnas.1209793110

Nicolis G and Prigogine I (1977) *Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations*, 1st Edn. New York: Wiley.

Nikitin M (2016) *The Origin of Life. From Nebula to Cell*. Naimark E and Surdin V (eds), Moscow: Alpina Digital, 542.

Noack L, Verseux C, Serrano P, Musilova M, Nauny P, Samuels T, Schwendner P, Simoncini E and Stevens A, 2015. Astrobiology from early-career scientists' perspective. *International Journal of Astrobiology* **14**, 533–535. https://doi.org/10.1017/S1473550415000233

Novikova N, Gusev O, Polikarpov N, Deshevaya E, Levinskikh M, Alekseev V, Okuda T, Sugimoto M, Sychev V and Grigoriev A (2011) Survival of dormant organisms after long-term exposure to the space environment. *Acta Astronautica, 17th IAA Humans in Space Symposium* **68**, 1574–1580. https://doi.org/10.1016/j.actaastro.2010.05.019

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Obridko VN, Ragul'skaya MV and Snytnikov VN (2024) Astronomical aspects of the origin and development of life. *Solar System Research* **58**, S1–S3. https://doi.org/10.1134/S0038094624601300

Obridko VN, Ragulskaya MV and Khramova EG (2020) Young Sun, galactic processes, and origin of life. *Journal of Atmospheric and Solar-Terrestrial Physics* **208**, 105395. https://doi.org/10.1016/j.jastp.2020.105395

Omelyansky VL (1911) Bacteriological examination of Sanga-Yuryakh mammoth and nearby soil. *Archives of Biological Sciences (in Russian)* **16**(4), 335.

Onstott TC, Ehlmann BL, Sapers H, Coleman M, Ivarsson M, Marlow JJ, Neubeck A and Niles P (2019) Paleo-rock-hosted life on Earth and the search on Mars: A review and strategy for exploration. *Astrobiology* **19**(10), 1230–1262. https://doi.org/10.1089/ast.2018.1960

Oparin AI (1975) Theoretical and experimental prerequisites of exobiology.

Oparin AI (1976) Evolution of the concepts of the origin of life, 1924-1974. *Origins of life* **7**, 3–8.

Orlov OI, Kotov OV and Smirnov YI (2023) Biomedical experiments on board the Russian segment of the ISS and prospective ROS. Presented at the Proceedings to the Third International Conference on the special occasion of the 25th anniversary of the ISS flight: Science on the International Space Station, Moscow: IKI RAS, pp. 194–196. https://doi.org/10.21046/ISS-2023

Oró J (1963) Synthesis of organic compounds by high-energy electrons. *Nature* **197**, 971–974. https://doi.org/10.1038/197971a0

Ozhiganov M, Medvedev M, Karteyeva V, Nakibov R, Sapunova U, Krushinsky V, Stepanova K, Tryastsina A, Gorkovenko A, Fedoseev G and Vasyunin A (2024) Infrared spectra of Solid HCN embedded in various molecular environments for comparison with the data obtained with JWST. *The Astrophysical Journal Letters*, **972**(1), L10. https://doi.org/10.3847/2041-8213/ad6d5c

Panov AD, Astapov II, Awad AK, Beskin GM, Bezyazeekov PA, Blank M, Bonvech EA, Borodin AN, Bruckner M, Budnev NM, Bulan AV, Chernov DV, Chiavassa A, Dyachok AN, Gafarov AR, Garmash AY, Grebenyuk VM, Gress OA, Gress TI, Grinyuk AA, Grishin OG, Horns D, Ivanova AL, Kalmykov NN, Kindin VV, Kiryuhin SN, Kokoulin RP, Kompaniets KG, Korosteleva EE, Kozhin VA, Kravchenko EA, Krivopalova AA, Kuzmichev LA, Kryukov AP, Lagutin AA, Lavrova MV, Lemeshev Y, Lubsandorzhiev BK, Lubsandorzhiev NB, Lukanov AD, Mirgazov RR, Mirzoyan R, Monkhoev RD, Osipova EA, Pakhorukov AL, Pan A, Pankov LV, Petrukhin AA, Podgrudkov DA, Poleschuk VA, Popova EG, Porelli A, Postnikov EB, Prosin VV, Ptuskin VS, Pushnin AA, Raikin RI, Razumov A, Rjabov E, Rubtsov GI, Sagan YI, Samoliga VS, Sidorenkov AY, Silaev AA, Silaev AA, Skurikhin AV, Satyshev I, Sokolov AV, Suvorkin Y, Sveshnikova LG, Tabolenko VA, Tanaev AB, Tarashansky BA, Ternovoy M, Tkachev LG, Tluczykont M, Ushakov N, Vaidyanathan A, Volchugov PA, Volkov NV, Voronin D, Wischnewski R, Yashin II, Zagorodnikov AV and Zhurov DP (2021) Search for astrophysical nanosecond optical transients with TAIGA-HiSCORE Array. *Physics of Atomic Nuclei* **84**, 1037–1044. https://doi.org/10.1134/S1063778821130251

Panov AD, Astapov II, Beskin GM, Bezyazykov PA, Blinov AV, Bonvech EA, Borodin A.N, Budnev NM, Bulan AV, Chernov PBDV, Chiavassa A, Dyachok AN, Gafarov AR, Garmash AY, Grebenyuk VM, Gress EO, Gress OA, Gress TI, Grinyuk AA, Grishin OG, Ivanova AL, Ivanova AD, Ilyushin MA, Kalmykov NN, Kindin VV, Kiryuhin SN, Kokoulin RP, Kompaniets KG, Korosteleva EE, Kozhin VA, Kravchenko EA, Kuzmichev LA, Kryukov AP, Lagutin AA, Lavrova MV, Lemeshev Y, Lubsandorzhiev BK, Lubsandorzhiev NB, Lukanov AD, Malakhov SD, Mirgazov RR, Monkhoev RD, Okyneva EA, Osipova EA, Pakhorukov AL, Pan A, Pankov LV, Petrukhin AA, Podgrudkov DA, Poddubny IA, Popova EG, Postnikov EB, Prosin VV, Pushnin AA, Raikin RI, Razumov AY, Rjabov E, Rubtsov GI, Samoliga VS, Shaikovsky AV, Sidorenkov AY, Silaev AA, Silaev AA, Skurikhin AV, Satyshev I, Sokolov AV, Sveshnikova LG, Tabolenko VA, Tanaev AB, Ternovoy M, Tkachev LG, Ushakov N, Volchugov PA, Volkov NV, Voronin DM, Yashin II, Zagorodnikov AV, Zhurov DP and Zirakashvili VN (2025) Four years of wide-field search for nanosecond optical transients with the TAIGA-HiSCORE cherenkov array. *Astron Rep* **69**, 433–456. https://doi.org/10.1134/S106377292570177X

Parfenov GP and Lukin AA (1973) Results and prospects of microbiological studies in outer space. *Space Life Sciences* **4**, 160–179. https://doi.org/10.1007/BF02626350

Parmon VN (2002) The origin of life: The prebiotic phase. *Herald of the Russian Academy of Sciences* **72**(11), 976–983.

Pavlov A, Cheptsov V, Tsurkov D, Lomasov V, Frolov D and Vasiliev G (2019) Survival of radioresistant bacteria on Europa's surface after pulse ejection of subsurface ocean water. *Geosciences* **9**, 9. https://doi.org/10.3390/geosciences9010009

Pavlov AK, Blinov AV and Konstantinov AN (2002) Sterilization of Martian surface by cosmic radiation. *Planetary and Space Science* **50**, 669–673. https://doi.org/10.1016/S0032-0633(01)00113-1

Pavlov AK, Shelegedin VN, Vdovina MA and Pavlov AA (2010) Growth of microorganisms in Martian-like shallow subsurface conditions: Laboratory modelling. *International Journal of Astrobiology* **9**, 51–58. https://doi.org/10.1017/S1473550409990371

Pecheritsyna SA, Rivkina EM, Akimov VN and Shcherbakova VA (2012) Desulfovibrio arcticus sp. nov., a psychrotolerant sulfate-reducing bacterium from a cryopeg. *International Journal of Systematic and Evolutionary Microbiology* **62**, 33–37. https://doi.org/10.1099/ijs.0.021451-0

Peltek SE, Bryanskaya AV, Uvarova YE, Rozanov AS, Ivanisenko TV, Ivanisenko VA, Lazareva EV, Saik OV, Efimov VM, Zhmodik SM, Taran OP, Slynko NM, Shekhovtsov S.V, Parmon VN, Dobretsov NL and Kolchanov NA (2020) Young «oil site» of the Uzon Caldera as a habitat for unique microbial life. *BMC Microbiology* **20**, 349. https://doi.org/10.1186/s12866-020-02012-1

Pérez-Hoyos S, Sánchez-Lavega A, García-Muñoz A, Irwin PGJ, Peralta J, Holsclaw G, McClintock WM and Sanz-Requena JF (2018) Venus upper clouds and the UV absorber from MESSENGER/MASCS observations. *Journal of Geophysical Research: Planets* **123**, 145–162. https://doi.org/10.1002/2017JE005406

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Petit J.R, Alekhina I and Bulat S (2005) Lake Vostok, Antarctica: Exploring a subglacial lake and searching for life in an extreme environment. In Gargaud M, Barbier B, Martin H and Reisse J (eds), *Lectures in Astrobiology: Volume I*. Berlin, Heidelberg: Springer, pp. 227–288. https://doi.org/10.1007/10913406_8

Pirogova PA, Zdobnova TA, Ivanova AV, Grinberg MA and Vodeneev VA (2024) Analysis of molecular mechanisms of chronic irradiation effects on electrical signals in wheat plants. *Biochemistry (Moscow), Supplement Series A: Membrane and Cell Biology* **18**(1), 36–43. https://doi.org/10.1134/S1990747824700053

Plaxco KW and Gross M (2021) *Astrobiology: An introduction*, 3rd Edn. Baltimore, US: Johns Hopkins University Press.

Podosokorskaya OA, Kadnikov VV, Gavrilov SN, Mardanov AV, Merkel AY, Karnachuk OV, Ravin NV, Bonch-Osmolovskaya EA and Kublanov IV (2013) Characterization of Melioribacter roseus gen. nov., sp. nov., a novel facultatively anaerobic thermophilic cellulolytic bacterium from the class Ignavibacteria, and a proposal of a novel bacterial phylum Ignavibacteriae. *Environmental Microbiology* **15**(6), 1759–1771. https://doi.org/10.1111/1462-2920.12067.

Popov AM, Berezhnoy AA, Borovička J, Labutin TA, Zaytsev SM and Stolyarov AV (2021) Tackling the FeO orange bands puzzle in meteor and airglow spectra through combined astronomical and laboratory studies. *Monthly Notices of the Royal Astronomical Society* **500**(4), 4296–4306. https://doi.org/10.1093/mnras/staa3487

Poturay VA and Kompanichenko VN (2019) Composition and distribution of saturated hydrocarbons in the thermal waters and vapor–water mixture of the Mutnovskii geothermal field and Uzon caldera, Kamchatka. *Geochemistry International* **57**, 74–82. https://doi.org/10.1134/S0016702919010087

Pozhvanov G, Sharova E and Medvedev S (2021) Microgravity modelling by two-axial clinorotation leads to scattered organisation of cytoskeleton in Arabidopsis seedlings. *Functional Plant Biology* **48**(10), 1062–1073. https://doi.org/10.1071/FP20225

Preunkert S, Legrand M, Stricker P, Bulat S, Alekhina I, Petit JR, Hoffmann H, May B and Jourdain B (2011) Quantification of dissolved organic carbon at very low levels in natural ice samples by a UV-induced oxidation method. *Environmental Science and Technology* **45**, 673–678. https://doi.org/10.1021/es1023256

Prigogine I (1955) *Introduction to Thermodynamics of Irreversible Processes, American Lecture series: Monograph in American lectures in Biochemistry and Biophysics*. Thomas Publisher.

Prigogine I and Lefever R (1973) Theory of dissipative structures. In Haken H (ed), *Synergetics: Cooperative Phenomena in Multi-Component Systems*. Wiesbaden: Vieweg+Teubner Verlag, pp. 124–135. https://doi.org/10.1007/978-3-663-01511-6_10

Prigogine I and Nicolis G (1977) *Self-Organization in Non-Equilibrium Systems*. New York, US: Wiley.

Punanova A, Vasyunin A, Caselli P, Howard A, Spezzano S, Shirley Y, Scibelli S and Harju J (2022) Methanol mapping in cold cores: Testing model predictions. *The Astrophysical Journal* **927**(2), 213. https://doi.org/10.3847/1538-4357/ac4e7d

Ragul'skaya MV (2024) Search for extraterrestrial life: The "Goldilocks Zone" vs. the "Snow Maiden Zone". *Solar System Research* **58**, S30–S39. https://doi.org/10.1134/S0038094624601099

Ragulskaya MV and Obridko VN (2017) The Sun and the biosphere: The paradoxes of 4 billion years of coexistence. *Radio Physics and Radio Astronomy* **22**, 276. https://doi.org/10.15407/rpra22.04.276

Raulin-Cerceau F (2016) Histoire de l'exobiologie. Histoire de la recherche contemporaine. La revue du Comité pour l'histoire du CNRS 42–51. https://doi.org/10.4000/hrc.1238

Rivkina E, Gilichinsky D, Wagener S, Tiedje J and McGrath J (1998) Biogeochemical activity of anaerobic microorganisms from buried permafrost sediments. *Geomicrobiology Journal* **15**(3), 187–193. https://doi.org/10.1080/01490459809378075

Rivkina E, Laurinavichius K, McGrath J, Tiedje J, Shcherbakova V and Gilichinsky D (2004) Microbial life in permafrost. *Advances in Space Research, Space Life Sciences: Search for Signatures of Life, and Space Flight Environmental Effects on the Nervous System* **33**, 1215–1221. https://doi.org/10.1016/j.asr.2003.06.024

Rivkina E, Shcherbakova V, Laurinavichius K, Petrovskaya L, Krivushin K, Kraev G, Pecheritsina S and Gilichinsky D (2007) Biogeochemistry of methane and methanogenic archaea in permafrost. *FEMS Microbiology Ecology* **61**, 1–15. https://doi.org/10.1111/j.1574-6941.2007.00315.x

Rivkina EM, Friedmann EI, McKay CP and Gilichinsky DA (2000) Metabolic activity of permafrost bacteria below the freezing point. *Applied and Environmental Microbiology* **66**, 3230–3233. https://doi.org/10.1128/AEM.66.8.3230-3233.2000

Rivkina EM, Spirina EV, Shatilovich AV, Shmakova LA and Abramov AA (2019) Permafrost microorganisms in space: Results of the exobiofrost experiment. *Earth's Cryosphere* **23**, 27–36. https://doi.org/10.21782/KZ1560-7496-2019-6(27-36)

Rozanov A, Astafieva M, Zaytseva L, Alfimova N and Felitsyn S (2016) Cyanobacteria(?) in iron banded formations of the Kursk magnetic anomaly. *Doklady Biological Sciences* **470**, 231–233. https://doi.org/10.1134/S0012496616050070

Rozanov AS, Bryanskaya AV, Malup TK, Meshcheryakova IA, Lazareva EV, Taran OP, Ivanisenko TV, Ivanisenko VA, Zhmodik SM, Kolchanov NA and Peltek SE (2014) Molecular analysis of the benthos microbial community in Zavarzin thermal spring (Uzon Caldera, Kamchatka, Russia). *BMC Genomics* **15** (Suppl 12), S12. https://doi.org/10.1186/1471-2164-15-S12-S12

Rozanov AY (2017) The history of the Earth is the history of life. In Obridko VN and Ragulskaya MV (eds), *Life and the Universe. Collective Monograph*. Moscow: VVM Publishing House, pp. 245–252.

Rozanov AY 2021. *Bacterial Paleontology*. Moscow: Russian Academy of Sciences.

Rozanov AY (2024) Some thoughts on discoveries in astrobiology. *Solar System Research* **58**, S4–S8. https://doi.org/10.1134/S0038094624601002

Rozanov AY, Lopatin AV and Snytnikov VN (2009) *Problems of the Origin of Life*. Moscow: PIN RAN.

Rozanov AY and Saprykin EA (2024) *Astrobiology*. Dubna: JINR.

Rozanov AY and Zavarzin GA (1998) Bacterial paleontology. In: I*nstruments, Methods, and Missions for Astrobiology. Presented at the Instruments, Methods, and Missions for Astrobiology*. SPIE, pp. 218–224. https://doi.org/10.1117/12.319848

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Rozanov AY, Zhegallo EA, Ushatinskaya GT, Shuvalova YV and Hoover RB (2002) Bacterial paleontology for astrobiology. In Instruments, Methods, and Missions for Astrobiology IV. Presented at the Instruments, Methods, and Missions for Astrobiology IV. Proceedings of SPIE'S International Symposium on Optical Science, Engineering, and Instrumentation, 19–24 July 1998, San Diego, US, 3441, pp. 283–294. https://doi.org/10.1117/12.454765

Saburov V, Kazakova E, Moiseev A, Kazakov E, Podlutskii M, Babina D, Korol M, Gorbatova I and Volkova P (2024) Combining clinostating and proton irradiation for modeling the space environment: A case study with a Chernobyl accession of Arabidopsis thaliana, *International Journal of Radiation Biology* **100**(12), 1696–1710. https://doi.org/10.1080/09553002.2024.2409665

Sachkov M and Kopylov E (2024) The world space observatory - ultraviolet mission: Science program and status report. In Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray. Proceedings of SPIE 13093, Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray, 21 August 2024, June 16–21, 2024, Yokohama, Japan, pp. 1082–1085. https://doi.org/10.1117/12.3020257

Sadovnichii VA, Alexandrov VV, Bugrov DI, Lemak SS, Pakhomov VB, Panasyuk MI, Petrov VL and Yashin IV (2018) The IMISS-1 experiment for recording and analysis of accelerations in orbital flight. *Space Science Reviews* **214**, 51. https://doi.org/10.1007/s11214-018-0470-0

Sagdeev RZ, Linkin VM, Kerzhanovich VV, Lipatov AN, Shurupov AA, Blamont JE, Crisp D, Ingersoll AP, Elson LS, Preston RA, Hildebrand CE, Ragent B, Seiff A, Young RE, Petit G, Boloh L, Alexandrov, Yu N, Armand NA, Bakitko RV and Selivanov AS (1986) Overview of VEGA Venus balloon in Situ meteorological measurements. *Science* **231**, 1411–1414. https://doi.org/10.1126/science.231.4744.1411

Saladino R, Bizzarri BM, Botta L, Šponer J, Šponer J.E, Georgelin T, Jaber M, Rigaud B, Kapralov M, Timoshenko GN, Rozanov A, Krasavin E, Timperio AM and Mauro ED (2017) Proton irradiation: A key to the challenge of N-glycosidic bond formation in a prebiotic context. *Scientific Reports* **7**, 14709. https://doi.org/10.1038/s41598-017-15392-8

Saladino R, Carota E, Botta G, Kapralov M, Timoshenko GN, Rozanov A, Krasavin E and Di Mauro E (2016) First evidence on the role of heavy ion irradiation of meteorites and formamide in the origin of biomolecules. *Origins of Life and Evolution of the Biosphere* **46**, 515–521. https://doi.org/10.1007/s11084-016-9495-0

Saladino R, Carota E, Botta G, Kapralov M, Timoshenko G.N, Rozanov A.Y, Krasavin E and Di Mauro E (2015) Meteorite-catalyzed syntheses of nucleosides and of other prebiotic compounds from formamide under proton irradiation. *Proceedings of the National Academy of Sciences* **112**, E2746–E2755. https://doi.org/10.1073/pnas.1422225112

Schwieterman EW, Olson SL, Pidhorodetska D, Reinhard CT, Ganti A, Fauchez TJ, Bastelberger ST, Crouse JS, Ridgwell A, Lyons TW (2022) Evaluating the plausible range of N_2O biosignatures on Exo-Earths: An integrated biogeochemical, photochemical, and spectral modeling approach. *The Astrophysical Journal* **937**, 109. https://doi.org/10.3847/1538-4357/ac8cfb

Semkova J, Bengin V, Koleva R, Krastev K, Matveychuk Y, Tomov B, Bankov N, Malchev S, Dachev T, Shurshakov V, Drobyshev S, Mitrofanov I, Golovin D, Kozyrev A, Litvak M and Mokrousov M (2024) New results of radiation study on board TGO ExoMars in 2018–2023 *Solar System Research* **58**(4), 367–376. https://doi.org/10.1134/S0038094624700291

Shatilovich AV, Tchesunov AV, Neretina TV, Grabarnik IP, Gubin SV, Vishnivetskaya TA, Onstott TC and Rivkina EM (2018) Viable nematodes from late pleistocene permafrost of the Kolyma River Lowland. *Doklady Biological Sciences* **480**, 100–102. https://doi.org/10.1134/S0012496618030079

Shcherbakova V, Chuvilskaya N, Rivkina E, Demidov N, Uchaeva V, Suetin S, Suzina N and Gilichinsky D (2013) Celerinatantimonas yamalensis sp. nov., a cold-adapted diazotrophic bacterium from a cold permafrost brine. *International Journal of Systematic and Evolutionary Microbiology* **63**, 4421–4427. https://doi.org/10.1099/ijs.0.045997-0

Shcherbakova V, Oshurkova V and Yoshimura Y (2015) The effects of perchlorates on the permafrost methanogens: Implication for autotrophic life on Mars. *Microorganisms* **3**, 518–534. https://doi.org/10.3390/microorganisms3030518

Shcherbakova V, Rivkina E, Pecheritsyna S, Laurinavichius K, Suzina N and Gilichinsky D (2011) Methanobacterium arcticum sp. nov., a methanogenic archaeon from Holocene Arctic permafrost. *International Journal of Systematic and Evolutionary Microbiology* **61**, 144–147. https://doi.org/10.1099/ijs.0.021311-0

Shcherbakova V, Yoshimura Y, Ryzhmanova Y, Taguchi Y, Segawa T, Oshurkova V and Rivkina E (2016) Archaeal communities of Arctic methane-containing permafrost. *FEMS Microbiology Ecology* **92**, fiw135. https://doi.org/10.1093/femsec/fiw135

Shcherbakova VA, Chuvil'skaya NA, Rivkina EM, Pecheritsyna SA, Suetin SV, Laurinavichius KS, Lysenko AM and Gilichinsky DA (2009) Novel halotolerant bacterium from cryopeg in permafrost: Description of Psychrobacter muriicola sp. nov. *Microbiology* **78**, 84–91. https://doi.org/10.1134/S0026261709010111

Shematovich V, Bisikalo D and Tsurikov G (2023) Non-thermal nitric oxide formation in the Earth's polar atmosphere. *Atmosphere* **14**, 1092. https://doi.org/10.3390/atmos14071092

Shematovich V, Bisikalo D, Tsurikov G and Zhilkin A (2024) Non-thermal processes of nitric oxide formation during precipitation of auroral electrons into the upper atmospheres of terrestrial planets. *Astronomy Reports* **68**, 843–864. https://doi.org/10.1134/S1063772924700744

Shklovsky IS (1960) Is communication with intelligent beings of other planets possible? *Priroda* **7**, 21–30.

Shklovsky IS (1987) Universe, life, mind, 6th ed., suppl. ed. Nauka Moscow

Shklovsky IS and Sagan C (1998) *Intelligent Life in the Universe*, 1st Edn. Avon, US: Emerson Adams Pr Inc.

Shnol SE (1973) Physicochemical aspect of the process of biological evolution. Possible determinism of the main stages of evolution by physical properties of the evolving system. *Journal of General Biology (in Russian)* **34**, 331.

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Shnol SE (1979) Factors determining the direction and speed of biological evolution In Mathematical Modeling of Biological Processes: Materials of the IV School on Mathematical Modeling. Nauka, Moscow, pp. 5–26.
Siegert MJ, Ross N and Le Brocq AM (2016) Recent advances in understanding Antarctic subglacial lakes and hydrology. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **374**, 20140306. https://doi.org/10.1098/rsta.2014.0306
Simakov M (2000) Dinitrogen as a Possible Biomarker for Exobiology: The Case of Titan, Proceedings of the 6th International Astronomical Union (IAU) Bioastronomy conference, Bioastronomy '99: A New Era in Bioastronomy, August 2–6, 1999, Hawaii, US, Vol. 213, pp. 333–338.
Simakov MB (2004) Possible biogeochemical cycles on Titan In Seckbach J (ed.), *Origins: Genesis, Evolution and Diversity of Life*. Dordrecht: Springer Netherlands, pp. 645–665. https://doi.org/10.1007/1-4020-2522-X_39
Simoneit BRT, Deamer DW and Kompanichenko V (2009) Characterization of hydrothermally generated oil from the Uzon caldera, Kamchatka. *Applied Geochemistry, Natural Low-pH Environments Unaffected by Human Activity* **24**, 303–309. https://doi.org/10.1016/j.apgeochem.2008.10.007
Skladnev D, Sorokin VV and Kotsyurbenko O (2023) Nanobiotechnological approach to detection and research metabolically active natural microbial communities as a new type of environmental monitoring for ecosystems. *Ecobiotech* **6**, 139–155. https://doi.org/10.31163/2618-964X-2023-6-3-139-155
Skladnev DA, Vasilyeva LV, Berestovskaya YY, Kotsyurbenko OR, Kalenov SV and Sorokin VV (2020) Detection of microorganisms in low-temperature water environments by in situ generation of biogenic nanoparticles. *Frontiers in Astronomy and Space Sciences* **7**, 59. https://doi.org/10.3389/fspas.2020.00059
Slobodkin A, Gavrilov S, Ionov V and Iliyin V (2015) Spore-forming thermophilic bacterium within artificial meteorite survives entry into the Earth's atmosphere on FOTON-M4 Satellite Landing Module. *PLoS One* **10**(7), e0132611. https://doi.org/10.1371/journal.pone.0132611
Slobodkin AI, Tourova TP, Kuznetsov BB, Kostrikina NA, Chernyh NA and Bonch-Osmolovskaya EA (1999) Thermoanaerobacter siderophilus sp. nov., a novel dissimilatory Fe(III)-reducing, anaerobic, thermophilic bacterium. *Int J Syst Bacteriol* **49**(Pt 4), 1471–1478. https://doi.org/10.1099/00207713-49-4-1471. PMID: 1055532
Snytnikov VN (2007a) Abiogenic synthesis of prebiotic matter for the Earth's biosphere as a stage of self-organization on an astrophysical and paleontological time scale. *Paleontological Journal* **41**, 473–480. https://doi.org/10.1134/S0031030107050012.
Snytnikov VN (2007b) Abiogenic protoplanetary synthesis of prebiotic substances. *Herald of the Russian Academy of Sciences* **77**(3), 218–226.
Snytnikov VN (2008) Astrocatalysis hypothesis for origin of life problem In Dobretsov N, Kolchanov N., Rozanov A and Zavarzin G (eds), *Biosphere Origin and Evolution*. Boston, MA: Springer US, pp. 45–53. https://doi.org/10.1007/978-0-387-68656-1_3
Snytnikov VN (2010) Astrocatalysis—Abiogenic synthesis and chemical evolution at pregeological stages of the Earth's formation. *Paleontological Journal* **44**, 761–777. https://doi.org/10.1134/S0031030110070063
Snytnikov VN, Dudnikova GI, Gleaves JT, Nikitin SA, Parmon VN, Stoyanovsky VO, Vshivkov VA, Yablonsky GS and Zakharenko VS (2002) Space chemical reactor of protoplanetary disk. *Advances in Space Research* **30**, 1461–1467. https://doi.org/10.1016/S0273-1177(02)00507-0.
Snytnikov VN and Parmon VN (2004) Does life create planets? *Science First Hand* **0**(1), 20–31.
Snytnikov VN, Vshivkov VA and Parmon VN (1996) Solar nebula as a global reactor for synthesis of prebiotic molecules. Presented at the 11th International Conference on the Origin of Life, Orleans, France, p. 65.
Soina VS, Mulyukin AL, Demkina EV, Vorobyova EA and El-Registan GI (2004) The structure of resting bacterial populations in soil and subsoil permafrost. *Astrobiology* **4**, 345–358. https://doi.org/10.1089/ast.2004.4.345.
Soina VS, Vorobiova EA, Zvyagintsev DG and Gilichinsky DA (1995) Preservation of cell structures in permafrost: A model for exobiology. *Advances in Space Research* **15**, 237–242. https://doi.org/10.1016/S0273-1177(99)80090-8.
Soina VS and Vorobyova EA (1996) Role of cell differentiation in high tolerance by prokaryotes of long-term preservation in permafrost. Advances in Space Research, Proceedings of the F3.1, F3.4, F2.4 and F3.8 Symposia of COSPAR Scientific Commission F 18, 97–101. https://doi.org/10.1016/0273-1177(96)00004-X.
Sorokin DY, Berben T, Melton ED, Overmars L, Vavourakis CD and Muyzer G (2014) Microbial diversity and biogeochemical cycling in soda lakes. *Extremophiles* **18**, 791–809. https://doi.org/10.1007/s00792-014-0670-9.
Spirin AS (1960) On macromolecular structure of native high-polymer ribonucleic acid in solution. *Journal of Molecular Biology* **2**, 436–446. https://doi.org/10.1016/S0022-2836(60)80054-X.
Spirin AS (2001) Protein biosynthesis, the world of RNA and the origin of life. *Herald of the Russian Academy of Sciences* **71**, 320–328.
Spirin AS (2004) The ribosome as an RNA-based molecular machine. *RNA Biology* **1**, 2–8. https://doi.org/10.4161/rna.1.1.889.
Spirin AS (2005a) RNA world and its evolution. *Молекулярная Биология* **39**, 550–556.
Spirin AS (2005b) Origin, possible forms of existence and sizes of primeval individuals. *Paleontological Journal* **4**, 25–32.
Spirin AS (2007) When, where, and in what environment could the RNA world appear and evolve? *Paleontological Journal* **41**, 481–488. https://doi.org/10.1134/S0031030107050024.
Spirin AS (2010) Ancient RNA world. *Paleontological Journal* **44**, 737–746. https://doi.org/10.1134/S003103011007004X.
Spirin AS (2013) The emergence of molecular machines as a prerequisite of the ancient RNA world evolution. *Paleontological Journal* **47**, 1016–1029. https://doi.org/10.1134/S0031030113090190.

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Spirina EV, Durdenko EV, Demidov NE, Abramov AA, Romanovsky VE, Rivkina EM (2017) Halophilic-psychrotrophic bacteria of an Alaskan cryopeg—A model for astrobiology. *Paleontological Journal* **51**, 1440–1452. https://doi.org/10.1134/S0031030117120036.

Sproß L, Scherf M, Shematovich VI, Bisikalo DV and Lammer H (2021). Life as the only reason for the existence of N_2–O_2-dominated atmospheres. *Astronomy Report* **65**, 275–296. https://doi.org/10.1134/S1063772921040077.

Sternfeld AJ (1935) La vie dans l'Univers. *La Nature* **2956**, 1–12.

Studinger M, Bell RE, Karner GD, Tikku AA, Holt JW, Morse DL, Richter TG, Kempf SD, Peters ME, Blankenship DD, Sweeney RE and Rystrom VL (2003) Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica. *Earth and Planetary Science Letters* **205**, 195–210. https://doi.org/10.1016/S0012-821X(02)01041-5.

Svetlichny VA, Sokolova TG, Gerhardt M, Ringpfeil M, Kostrikina NA and Zavarzin GA (1991) Carboxydothermus hydrogenoformans gen. nov., sp. nov., a CO-utilizing thermophilic anaerobic bacterium from hydrothermal environments of Kunashir Island. *Systematic and Applied Microbiology* **14**(3), 254–260. https://doi.org/10.1016/S0723-2020(11)80377-2.

Tarasov K, Kravchenko E, Zarubin M and Yakhnenko A (2024) Deep underground metagenome-assembled genomes from hydrothermal spring. *Microbiology Resource Announcements* **13**(10), e00574–24. https://doi.org/10.1128/mra.00574-24.

Tikhov GA (1949) Astrobotanika. Osnovnye Trudy, Izd. AN KazakhSSR, Alma-Ata, 4:3-29.

Tikhov GA (1953) Astrobiology. Molodaya Gvardiya, Moscow, 68P.

Tikhov GA (1956) Prospects of a new science. *Science and Life (in Russian)* **11**, 24.

Tselmovich VA (2020) Composition and microscopic features of background cosmic dust from peat. In Votyakov S, Kiseleva D, Grokhovsky V and Shchapova Y (eds), *Minerals: Structure, Properties, Methods of Investigation*. Cham: Springer International Publishing, pp. 253–259. https://doi.org/10.1007/978-3-030-00925-0_37

Tselmovich VA, Amelin II, Gusiakov VK, Kirillov VE and Kurazhkovskii AY (2023) On the possible cometary nature of the uchur cosmic body (Fall 3.08. 1993). Advances in Geological and Geotechnical Engineering Research 5, 16–24. https://doi.org/10.30564/agger.v5i3.5705

Tselmovich VA, Kurazhkovskii AY, Kazansky AY, Shchetnikov AA, Blyakharchuk TA and Philippov DA (2019) Studying the dynamics of cosmic dust flux on the Earth's surface from peat deposits. *Izvestiya, Physics of the Solid Earth* **55**, 517–527. https://doi.org/10.1134/S1069351319030108

Tselmovich VA, Kuzina DM, Muftakhetdinova RF, Yakovlev GA, Ezhov VF, Chetverikov OY and Bulat SA (2025) The first detection of tin and copper particles in the magnetic component of space matter collected from Antarctica by a magnetic trap. ВЕСЭМПГ-2025, avril 15-16. GeoChi, Moscow, Russia.

Tsurikov G, Bisikalo D, Shematovich V and Zhilkin A (2024) Searching for biomarkers with Spektr-UF observatory: Nitric oxide molecule in atmospheres of exoplanets near the active host stars. *Astronomy Reports* **102**(2), 130–147.

Tsurikov GN and Bisikalo DV (2023) NO biomarker: Transmission and emission methods for its potential detection in exoplanet atmospheres with spektr-UF (WSO-UV). *Astronomy Reports* **67**, 1123–1138. https://doi.org/10.1134/S1063772923110100

Tsurikov GN, Sychevsky SG, Shmagin VE, Nikonorov IN and Shustov BM (2024) "Spektr-UF" exposure calculator: The first web version for users. *INASAN Science Reports* **9**, 12–31. https://doi.org/10.51194/INASAN.2024.9.1.003

Tsyrenova DD, Bryanskaya AV, Namsaraev ZB and Akimov VN (2011) Taxonomic and ecological characterization of cyanobacteria from some brackish and saline lakes of Southern Transbaikal Region. *Microbiology* **80**, 216–227. https://doi.org/10.1134/S0026261711020160

Tverdislov VA (2013) Chirality as a primary switch of hierarchical levels in molecular biological systems. *Biophysics* **58**, 128–132. https://doi.org/10.1134/S0006350913010156

Tverdislov VA and Malyshko EV (2016) Chiral quality as a factor of hierarchical structure formation in the molecular biology evolution. Complexity. Reason. Post-non-classical 78–83.

Unger M and Polt W (2017) The knowledge triangle between research, education and innovation – A conceptual discussion. *Foresight and STI Governance* **11**, 10–26. https://doi.org/10.17323/2500-2597.2017.2.10.26

Vandaele AC, Aoki S, Bauduin S, Daerden F, Fedorova A, Giuranna M, Korablev O, Lefèvre F, Määttänen A, Montmessin F, Patel MR, Smith M, Trompet L, Viscardy S, Willame Y, and Yoshida N (2024) Composition and chemistry of the martian atmosphere as observed by Mars Express and ExoMars trace gas orbiter *Space Science Reviews* **220**(7), 75. https://doi.org/10.1007/s11214-024-01109-7

Venera-D Landing Sites Selection and Cloud Layer Habitability Workshop Report – October 2-5 (2019) – Moscow, Russia https://vexag.org/pdf/venerad_2019wkshp_techrp_cover_21july20_v12final.pdf

Venera-D: Venus Cloud Habitability System Workshop Report – November 30 – December 3 (2021) – Virtual https://vexag.org/pdf/venera-d-workshop-2021-final-report.pdf

Venus (2021) https://doi.org/10.1089/ast.2021.0142

Venus 2 (2024) https://doi.org/10.1089/ast.2024.2902

Vishnivetskaya TA, Mironov VA, Abramov AA, Shcherbakova VA and Rivkina EM (2022) Biogeochemical characteristics of Earth's volcanic permafrost: An analog of extraterrestrial environments. *Astrobiology* **22**, 812–828. https://doi.org/10.1089/ast.2021.0137

Vishnivetskaya TA, Petrova MA, Urbance J, Ponder M, Moyer CL, Gilichinsky DA, Tiedje JM (2006) Bacterial community in ancient Siberian permafrost as characterized by culture and culture-independent methods. *Astrobiology* **6**, 400–414. https://doi.org/10.1089/ast.2006.6.400

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Vishnivetskaya TA, Spirina EV, Shatilovich AV, Erokhina LG, Vorobyova EA and Gilichinsky DA (2003) The resistance of viable permafrost algae to simulated environmental stresses: implications for astrobiology. *International Journal of Astrobiology* **2**, 171–177. https://doi.org/10.1017/S1473550403001575

Vorobyova E, Soina V, Gorlenko M, Minkovskaya N, Zalinova N, Mamukelashvili A, Gilichinsky D, Rivkina E and Vishnivetskaya T (1997) The deep cold biosphere: Facts and hypothesis. *FEMS Microbiology Reviews* **20**, 277–290. https://doi.org/10.1111/j.1574-6976.1997.tb00314.x

Vorobyova EA, Cheptsov VS, Osipov GA, Kotsyurbenko OR and Soina VS (2018) Gamma-IR resistance of bacteria in soil and permafrost. *Paleontological Journal* **52**, 1204–1216. https://doi.org/10.1134/S0031030118100167

Vorobyova EA, Soina VS and Mulukin AL (1996) Microorganisms and enzyme activity in permafrost after removal of long-term cold stress. Advances in Space Research, Proceedings of the F3.1, F3.4, F2.4 and F3.8 Symposia of COSPAR Scientific Commission F, 11–21 July 1994, Hamburg, Germany, 18, 103–108. https://doi.org/10.1016/0273-1177(96)00005-1

Watson J and Crick F (1953) Molecular structure of nucleic acids; a structure for deoxyribose nucleic acid. *Nature*, **171**(4356): 737–238.

Webster CR, Mahaffy PR, Atreya SK, Moores JE, Flesch GJ, Malespin C, McKay CP, Martinez G, Smith CL, Martin-Torres J, Gomez-Elvira J, Zorzano M-P, Wong MH, Trainer MG, Steele A, Archer D, Sutter B, Coll PJ, Freissinet C, Meslin P-Y, Gough RV, House CH, Pavlov A, Eigenbrode JL, Glavin DP, Pearson JC, Keymeulen D, Christensen LE, Schwenzer SP, Navarro-Gonzalez R, Pla-García J, Rafkin SCR, Vicente-Retortillo Á, Kahanpää H, Viudez-Moreiras D, Smith MD, Harri A-M, Genzer M, Hassler DM, Lemmon M, Crisp J, Sander SP, Zurek RW and Vasavada AR (2018) Background levels of methane in Mars' atmosphere show strong seasonal variations *Science* **360**(6393), 1093–1096. https://doi.org/10.1126/science.aaq0131

Webster CR, Mahaffy PR, Pla-Garcia J, Rafkin SCR, Moores JE, Atreya SK, Flesch GJ, Malespin CA, Teinturier SM, Kalucha H, Smith CL, Viúdez-Moreiras D and Vasavada AR (2021) Day-night differences in Mars methane suggest nighttime containment at Gale crater. *Astronomy and Astrophysics* **650**, A166. https://doi.org/10.1051/0004-6361/202040030

Widemann T, Smrekar SE, Garvin JB, Straume-Lindner AG, Ocampo AC, Schulte MD, Voirin T, Hensley S, Dyar MD, Whitten JL, Nunes DC, Getty SA, Arney GN, Johnson NM, Kohler E, Spohn T, O'Rourke JG, Wilson CF, Way MJ, Ostberg C, Westall F, Höning D, Jacobson S, Salvador A, Avice G, Breuer D, Carter L, Gilmore MS, Ghail R, Helbert J, Byrne P, Santos AR, Herrick RR, Izenberg N, Marcq E, Rolf T, Weller M, Gillmann C, Korablev O, Zelenyi L, Zasova L, Gorinov D, Seth G, Rao CVN and Desai N (2023) Venus evolution through time: Key science questions, selected mission concepts and future investigations. *Space Science Reviews* **219**, 56. https://doi.org/10.1007/s11214-023-00992-w

Wiebe DZ (2024) Cosmic rays as an astrochemical factor. Physics of Space: Proceedings of the 51st All-Russian Student Scientific Conference with International Participation. Ekaterinburg, Jan 29–Feb 2, pp. 6–17. https://doi.org/10.15826/B978-5-7996-3848-1.01

Wiebe DZ, Molyarova TS, Akimkin VV, Vorobyov EI and Semenov DA (2019) Luminosity outburst chemistry in protoplanetary discs: Going beyond standard tracers. *Monthly Notices of the Royal Astronomical Society* **485**, 1843–1863. https://doi.org/10.1093/mnras/stz512

Wiebe DZ and Stolyarov AV (2021) Advances and perspectives of astrochemistry in laboratory. *Zemlya i Vselennaya* **2**, 19–29. https://doi.org/10.7868/S004439482102002X

Woese C (1998) The universal ancestor. *Proceedings of the National Academy of Sciences* **95**, 6854–6859. https://doi.org/10.1073/pnas.95.12.6854

Wright A and Siegert M (2012) A fourth inventory of Antarctic subglacial lakes. *Antarctic Science* **24**, 659–664. https://doi.org/10.1017/S095410201200048X

Yakimov MM, Marturano L, Kondrasheva KV, Gavrilov SN, Klyushin GS, Umruzokov AA, Mamarasulov BD, Crisafi F, Smedile F, La Spada G, La Cono V, Messina E and Davranov KD (2025) Diversity and bioprospecting of culturable plant-associated bacteria from saline soils in the Aydarkul Lake region, Uzbekistan. *Eurasian Soil Science* **58**, 206. https://doi.org/10.1134/S1064229325603361

Zaar EI, Zelikson VG, Kitaigorodsky MG, Lozina-Lozinsky LK, Koshelev GV and Rybin MA (1970) The apparatus "Photostat-I" for simulating Martian environmental conditions. *Life Sciences in Space Research* **8**, 62–67.

Zaitsev MA, Gerasimov MV, Safonova EN and Vasiljeva AS (2016) Peculiarities in the formation of complex organic compounds in a nitrogen–methane atmosphere during hypervelocity impacts. *Solar System Research* **50**, 113–129. https://doi.org/10.1134/S0038094616020076

Zaitsev MA, Gerasimov MV, Vasiljeva AS, Korochantsev AV, Ivanova MA and Lorenz CA (2018) On the simularity of volatile organics patterns in meteorites and in impact-induced vapor plume. *81st Annual Meeting of the Meteoritical Society* **81** (2067), 6208.

Zaitseva SV, Abidueva EY, Namsaraev BB, Wang L, Wu L (2014) Microbial community of the bottom sediments of the Brackish Lake Beloe (Transbaikal region). *Microbiology* **83**, 861–868. https://doi.org/10.1134/S0026261714060216

Zaitseva SV, Abidueva EY, Radnagurueva AA, Bazarov SM and Buryukhaev SP (2018) Structure of microbial communities of the sediments of Alkaline Transbaikalia Lakes with different salinity. *Microbiology* **87**, 559–568. https://doi.org/10.1134/S0026261718040185

Zarubin M, Azorskaya T, Kuldoshina O, Alekseev S, Mitrofanov S and Kravchenko E (2023) The tardigrade Dsup protein enhances radioresistance in Drosophila melanogaster and acts as an unspecific repressor of transcription. *iScience* **26**(7), 106998, 1–19. https://doi.org/10.1016/j.isci.2023.106998

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press

Zarubin M, Gangapshev A, Gavriljuk Y, Kazalov V and Kravchenko E (2021a) First transcriptome profiling of D. Melanogaster after development in a deep underground low radiation background laboratory. *PLoS One* **16**(8), e0255066. http://doi.org/10.1371/journal.pone.0255066.

Zarubin M, Murugova T, Ryzhykau Y, Ivankov O, Uversky VN and Kravchenko E (2024) Structural study of the intrinsically disordered tardigrade damage suppressor protein (Dsup) and its complex with DNA. *Scientific Reports* **14**(1), 22910. https://doi.org/10.1038/s41598-024-74335-2.

Zarubin M, Pikalov V and Gangapshev A (2025) BioMuon experiment (Bioμ): Review of studies on biological impact of high-energy muons and research prospects. *International Journal of Radiation Biology* **101**(12), 1–12. https://doi.org/10.1080/09553002.2025.2560882

Zarubin MP, Kuldoshina OA and Kravchenko EV (2021b) Biological effects of low background radiation: Prospects for future research in the low-background laboratory DULB-4900 of Baksan neutrino observatory INR RAS. *Physics of Particles and Nuclei* **52**(1), 19–30. https://doi.org/10.1134/S1063779621010056.

Zavarzin GA (1973) Bacteria on volcanoes. *Priroda* **7**, 66–71.

Zavarzin GA (1993a) Epicontinental soda reservoirs as putative relict biotopes for the formation of terrestrial biota. *Microbiology* **62**, P.789–800.

Zavarzin GA (1993b) A development of microbial communities in the Earth history. In Rozanov AY (ed), *Problems of the Pre-Antropogenic Evolution of the Biosphere*. Moscow: Nauka, pp. 212–222.

Zavarzin GA (1995) Anti-market in nature. *Priroda* **3**, 46–60.

Zavarzin GA (2001) Formation of the biosphere. *Herald of the Russian Academy of Sciences* **71**(11), 988–1001.

Zavarzin GA (2004a) Microbes hold the sky. *Nauka iz pervykh ruk* **2**, 21–27.

Zavarzin GA (2004b) The future is selected by the past. *Vestnik RAN* **74**, 813–822.

Zavarzin GA (2007) Development of soda environments as a global process. In Galchenko VF (ed), *Proceedings of the Winogradsky Institute of Microbiology*. Moscow: Nauka, pp. 8–57.

Zavarzin GA (2015) *Selected Works*. Moscow: MAX Press.

Zavarzin GA and Karpov GA (1982) The role of bacterial factors in modern hydrothermal mineral formation of the Uzon caldera. *Reports of the USSR Academy of Sciences (in Russian)* **264**, 244–247.

Zavarzin GA, Karpov GA, Gorlenko MV, Golovacheva RS, Gerasimenko LM, Bonch-Osmolovskaya EA and Orleanskiy VK (1989) *Caldera Microorganisms*. Moscow: Nauka.

Zavarzina DG, Maslov AA, Merkel AY, Kharitonova NA, Klyukina AA, Baranovskaya EI, Baydariko EA, Potapov EG, Zayulina KS, Bychkov AY, Chernyh NA, Bonch-Osmolovskaya EA and Gavrilov SN (2025) Analogs of Precambrian microbial communities formed de novo in Caucasian mineral water aquifers. *mBio* **16**, e02831–24, https://doi.org/10.1128/mbio.02831-24

Zeleny LM (2022) At the origins of the study of planetary atmospheres and the philosophy of Russian cosmism. *Zemlya i Vselennaya* **3**, 63–82.

Zvyagintsev DG, Gilichinsky DA, Blagodatsky SA, Vorob'eva EA, Khlebnikova GM and Arkhangelov AA (1985) Duration of the microbial surviving in the permafrost deposits and buried soils. *Mikrobiologiya* **54**, 155–161.

https://doi.org/10.1017/S1473550426100305 Published online by Cambridge University Press