Vladimir Ivanovich Vernadsky: The Science of the Biosphere And Astrobiology

by Academician M. Ya. Marov

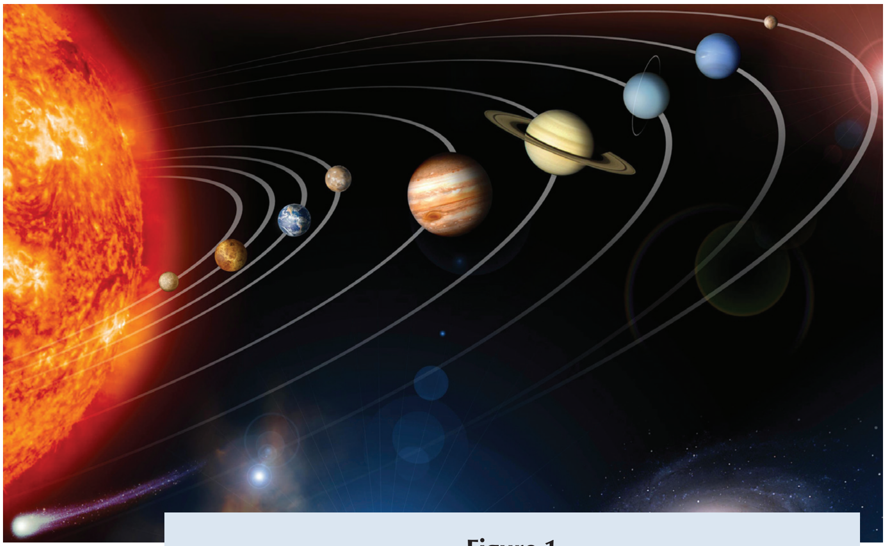
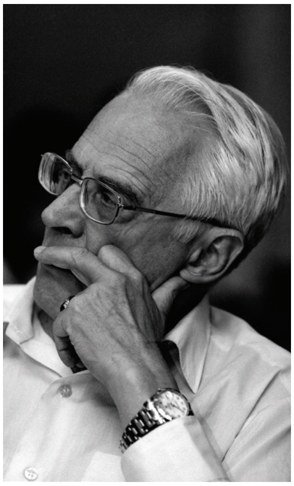


Figure 1
Schematic view of the Solar System and planetary nebula to be left behind after the Sun (a G2 star with the lifetime about 10 billion years) exhausts its nuclear fuel, approximately five billion years from now, according to the Encyclopedia of Astronomy and Astrophysics *(2002).*

V.I. Vernadsky's Biosphere

Vernadsky greatly expanded and developed the concept of the biosphere. He imbued that very word—first proposed by the French scientist Jean-Baptiste Lamarck in 1802, in his book *Hydrogeology*, to denote the totality of our planet's living organisms—with much deeper meaning. Now the term "biosphere" went far beyond its simple definition as the sum total of sedimentary rocks created by organisms, the sense in which it had been used in the late 19th century by the Austrian geologist Eduard Suess in *The Origin of the Alps,* and the German geologist Johannes Walther, well-known for his works on lithology. The term was understood in a new way after the 1926 publication of Vernadsky's *The Bio-*



Academician Marov is the head of the Department of Cosmochemistry, at the Russian Academy of Sciences' Vernadsky Institute of Geochemistry and Analytical Chemistry. His principal scientific interests have been in the fundamental problems of hydrodynamics, gas kinetics, and space physics, with an application to Solar System studies and planetary cosmogony. He has authored more than 250 technical articles, and 15 books and monographs. This is the second part of his paper, translated by William Jones, with Rachel Douglas and Susan Welsh.

In the first part, published in the Spring 2013 issue of 21st Century Science & Technology, *Academician Marov dealt with Vernadsky's career and with some of the important contributions he had made in the numerous fields in which he was engaged: mineralogy, hydrology, radiochemistry and biogeochemistry. But Vernadsky, Academician Marov noted, in his study of geochemistry and of life here on Earth always kept in view the cosmic dimensions of Earth's origin, and underlined the fact that the knowledge acquired in our examination of the Earth's biosphere would enable us to move forward as we cast our view to that broader Cosmos, in the study of life in the Universe in astrobiology, which he takes up in this issue.*

sphere; the body of his thought on the biosphere appeared most fully in the posthumously published books *The Chemical Structure of the Earth's Biosphere and Its Surroundings* (1965) and *Living Matter* (1978), in which were assembled some of his reflections and works on the subject that had not been published during his lifetime.

Vernadsky identified the boundaries of the biosphere as well as its composition, energetics, and dynamics. He included in the biosphere the upper part of the lithosphere to a depth of 2-3 km, which contains living bacteria, the hydrosphere, and the lower part of the atmosphere. Within the biosphere he distinguished two component types of matter: minerals, which he termed "inert," and living matter. The morphology of inert matter (its chemical composition and physical state) is preserved unchanged in the course of geological time, while living matter, both in totality and in its individual forms, undergoes continual change in the process of the biosphere's evolution as an integrated system. Vernadsky considered living matter, the active component of the biosphere, to be the carrier of free energy in the biosphere's geochemical processes, viewing certain forms of homogeneous living matter that have remained unchanged for billions of years (such as some species of *Radiolaria* that have been unchanged since the Algonkian Era, or the genus *Lingula*, unchanged since the Cambrian Era) as exceptions. At the same time, he rejected the existence of any special zones between living and non-living matter, advancing the empirical generalization that "there are no transitions between living and inert natural bodies of the biosphere: the boundary between them has been sharp and clear during the entire span of geological history. … Matter in the biosphere is comprised of two states, which differ materially and energetically—living and inert."

Vernadsky viewed the biosphere and the conditions under which life emerged on our planet as an inseparable component of a certain structure of the Earth's crust and its degree of organization. He based this conception on geology and geochemistry, and the tremendous amount of empirical material accumulated by these sciences. Geology had made it possible to formulate the scientific question of the origin of the biosphere, while geochemistry provided a reliable determination of the conditions necessary for the creation of the biosphere and the emergence of life. In his judgment, the task of geochemistry was the "study of the history of the chemical elements within the bounds of our planet," and this new branch of natural science was in fact established through Vernadsky's work. "We are obtaining a new and firm basis," he wrote, "resting on the tremendous amount of empirical material from geology and geochemistry. Geology now allows us scientifically to pose the question of the origin of the biosphere, and geochemistry to make a scientific determination of the conditions which life must satisfy in order for the biosphere to come into being." The emergence of the biosphere, therefore, is linked to a geochemically valid solution to the problem of the polyphyletic origin of the main taxa: that is, a close interrelationship among the diverse forms of primordial life, as a unified planetary phenomenon on the scale of the biosphere.

Vernadsky thought that the continuous migration of atoms in the Earth's crustal layer was biogenic to a significant degree, i.e., that it was caused by the geochemical energy of living matter (the energy of life), connected first and foremost with the processes of alimentation and respiration of living organisms. He came to the surprising conclusion that living matter changes the structure of inert matter, acting upon chemical compounds and even upon atomic states, and inducing a stable state of carbon in organic molecules under the thermodynamic conditions of the biosphere. Vernadsky thought that living organisms should be characterized quantitatively in the same way as other bodies, according to their atomic composition, mass, and energy, and that the mass of living matter and its average chemical composition in the biosphere are not changed or disrupted by the process of evolution. This approach to the biogeochemical function of the biosphere means that the biogenic migrations of atoms do not change either quantitatively or qualitatively, in spite of sharp changes in the morphological structure of living matter in the course of geological time. At the same time, the evolution of life forms results in an increase of geochemical energy and changes the character of the biosphere, particularly in connection with the "whirlwind of biogenic migration of atoms" resulting from the growth of civilization it has engendered, without, however, any noticeable violation of the regularities of the more powerful mechanism of the Earth's crust.

Solar and chemical energy serve as the original source of the energy of life. The absorption of solar energy by photoautotrophs—the living matter that uniquely transforms solar energy into chemical energy and distributes it throughout the planet—is one of the most important functions of living matter in the biosphere. And this is the basic energy source for exogenous geochemical and geological processes. In other words, living matter, transforming solar radiation, draws inorganic material into continuous circulation. This idea is central to the concept of biogeochemistry, which Vernadsky introduced. In it he included the functions of the exchange of matter—respiration, alimentation, creation of the body mass of organisms, their movements and the work they perform, and even grander undertakings on the scale of human communities. "Biogenic migration is of extraordinary importance in the structure of the biosphere," he wrote, "Suffice it to mention that the free oxygen on our planet is created almost entirely by the geochemical energy of life—by the photochemical processes of the plant world."

In his writings, Vernadsky repeatedly emphasized the biogenic nature of gaseous and liquid masses and their connection with living matter, which exerts a tremendous influence on the chemical composition of the atmosphere and hydrosphere. "Living organisms," he wrote, "determine by their life the chemistry of the sea, in particular the composition of seawater, and the character of natural waters—from freshwater, lake, and some mineral sources." This regulation is accomplished both by land-based living matter, which determines the chemical qualities of the river waters flowing into the ocean, and by marine living matter, which produces selective precipitation of the chemical elements which enter the ocean. In other words, the biogenic migration of the chemical elements on the Earth's surface in the biosphere has been accomplished with the direct participation of living matter throughout all geological time. Its manifestation within the mass of the planet's matter, like the phenomena of life, must increase in geometric progression.

Proceeding from the empirical generalizations of geochemistry, Vernadsky advanced three propositions, asserting that the existence of the biosphere and the appearance of living matter were inseparable. He believed that the biosphere was not an accidental formation, but rather a "distinctive lawful mechanism," whose individual parts are connected and mutually conditioned, and which has the property of being organized. Its state of organization is determined by biogenic cycles of the atoms of chemical elements, and not all of the elements are characterized by reversibility; some of them constantly exit from circulation. This thesis is extremely important, in that it precludes a chaotic state and proposes the self-regulation of the biosphere as a paradigm of the emergence of self-organization in the natural environment. It proposes the existence in the biosphere of orderly processes with historically developed forms of matter and energy transfer. And this means that it is possible in principle to describe the structure of living nature and its interaction processes with precision, on the basis of mathematical models. Another important proposition was his conception of the totality of all the organisms constituting life, as inseparable parts of this mechanism, which permeates the entire biosphere. Finally, he held that the basic features of the structure and mechanism of the interactions on which the biosphere is based were stable and constant, and that it had been a stable system in dynamic equilibrium over the billions of years since its origin, in the Archean Eon, similar to the stability and immutability of the configuration of the Solar System (Fig. 1). The absence of any restructuring of the biosphere, in the course of all geological time, essentially reflects "a scientific conception of the immutability and stability of all natural processes."

Closed biotic cycles, of which nutrient (trophic) interactions are an important component, are a condition for the stability of the biosphere and, at the same time, represent the basis of life as a biospheric process. Such processes as the growth of the biomass of organisms, the assimilation of matter, energy exchange, the differentiation/migration of the chemical elements, and the synthesis and breakdown of organic compounds at all stages of the trophic cycle in biocenoses, are all connected with these biotic cycles. The bacteria and plants of the early biosphere (the autotrophs) utilized carbon from atmospheric carbon dioxide and possessed no mechanism for nitrogen fixation or photosynthesis, nor did they have fermentation systems, which would have provided energy through the hydrolytic decomposition of their internal structures. These processes arose later in the course of evolution, and our modern animal world (heterotrophs), with its extraordinarily complex organization, consumes a wide array of organic and inorganic materials. Trophic relations essentially delimit the distribution and size of the population of any species, as well as its evolutionary development.

Vernadsky estimated the quantity of biomass at between one and ten thousand trillion tons, presuming that this has changed in the process of biological evolution together with the forms of life, starting from a tiny mass of blue-green algae and the first terrestrial plants in the Devonian period around 330 million years ago, through the greatly expanding mass of the Carboniferous swamp forests, and into the modern historical period. Vernadsky studied the geochemical energy of living matter, based on the quantitative patterns of its distribution in the biosphere and of the reproduction of various groups of organisms.

Comparing the energy balance of Earth with that of other planets of the Solar System, Vernadsky singled out the biosphere as the domain in which solar electromagnetic energy is transformed into mineral resources (which he called *solid solutions*) in the form of deposits of brown coal and hard coal, combustible shales, oil and gas, which are not found in the weathering crust or outside the biosphere. He estimated the magnitude of the energy of these combustible compounds—living matter of the Earth, produced solely by terrestrial vegetation—to be on the order of 10^{18}–10^{19} kcal. "Here we are dealing with a new process," Vernadsky wrote, "with the slow penetration of the radiant energy of the Sun, reaching the surface of the Earth, into the planet's interior. In this way, living matter changes the biosphere and the Earth's crust. It continually deposits in the Earth's crust a portion of the chemical elements that have passed through it, creating vast strata of vadose minerals,[1] unknown apart from living

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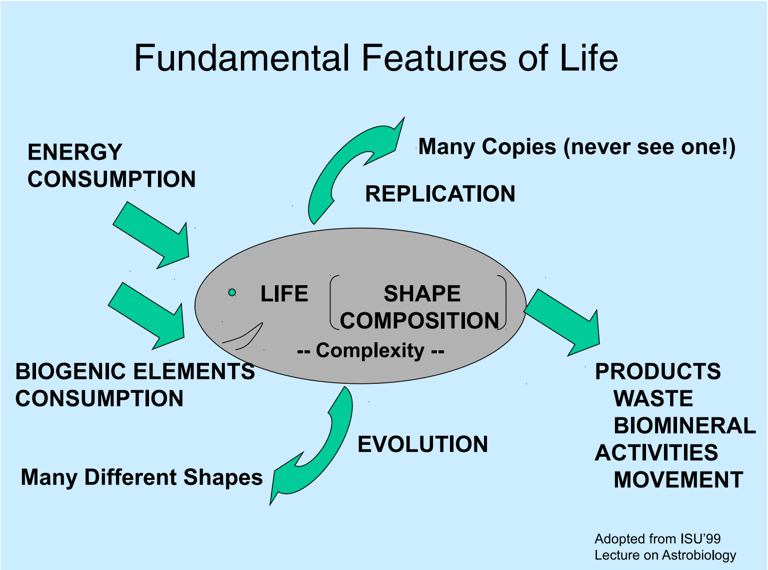
[1] Minerals enriched with manganese ("wad" or "bog manganese"). Vernadsky attributes great significance to the role of living matter and water in its concentration on the Earth's surface. In the geochemical history of manganese, biochemical reactions connected to bacteria

matter, or penetrating the inert matter of the biosphere with fine residual dust." Vernadsky considered the stratified part of the Earth's crust (the Earth's sedimentary envelope) to be the remnant of earlier biospheres, and thought that even the granite-gneiss layer had been formed as a result of the metamorphism and remelting of rocks formed earlier under the influence of living matter. In other words, only basalts and the other main magmatic rocks are abyssal, their formation being unconnected to the biosphere. Insofar as life has never been present on the Moon or Venus, no granite-like rocks have been found there, but only the basic magmatic rocks.

Thus, Vernadsky's biosphere is a global ecosystem in which connections among the gaseous, liquid, and solid envelopes are regulated by living matter, and the biosphere's basic properties result from the activity of these envelopes. Life, therefore, is Earth's planetary constant, which is closely bound up with the structure and the function of these envelopes. "Life is not . . . an external random occurrence on the surface of the Earth," he said. "Never in all geological time have there been azoic[2] geological epochs."

Figure 2



Adopted from ISU'99
Lecture on Astrobiology

Schematic representation of the fundamental features of life.

Source: International Space University (ISU)

On the Origin of Life

We see that the very presence of living matter on Earth was Vernadsky's starting point for developing his scientific conception of a biosphere literally permeated by everything living, and of the conditions under which the appearance of this matter on our planet became possible, although this intriguing problem itself—the question of the origin of life—remains unresolved to this day.

In his report "On the Conditions for the Appearance of Life on Earth," presented in 1931 to the Leningrad Society of Naturalists and the Soviet Academy of Sciences, Vernadsky said:

> The conditions under which life appeared on our planet must be posed in realistic circumstances. Life is known to us, under real circumstances, only as an inseparable component of a certain structure of the Earth's crust. One of the geospheres of our planet, the biosphere, is such a form of organization. The conditions that determined the first appearance of life on Earth are the same ones that determined the creation or origin of the biosphere on our planet. Scientifically, the question of the origin of life on Earth is therefore reduced to the question of the origin of the Earth's biosphere. ... An organism removed from the biosphere is not something real, but rather an abstract logical construct.

In other words, life can arise only under certain physicochemical conditions, and the conditions that allowed for the appearance of life on Earth are those which led to the origin of the biosphere.

Life requires liquid water, the presence of biogenic elements, and available sources of free energy. Among the fundamental properties of life, distinguishing living from non-living matter, are the consumption of energy and natural substances, replication (reproduction), secretion of wastes, active biomineral exchange, and evolution (Fig. 2). The basic question we are addressing concerns the origin of life—the origin of the transition from prebiotic chemistry to the processes of metabolism, replication, and transmission of genetic information, since life in the modern sense has to be defined as a functional system, capable of processing and transmitting information on the molecular level.

Vernadsky's view was that the main marker of the origin

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play a major role, particularly autotrophic bacteria, which owe their existence to chemical energy (the energy of oxidation), and are capable of concentrating manganese to a level of 7%. More developed organisms (for instance, some marine plants, lichens, various fungi) concentrate manganese to a level of 1%.

[2] Lacking life.

of life was the appearance in the biosphere of extremely diverse geochemical functionality, supplied by the totality of many species and various morphological classes of organisms, which could accomplish cyclical mass-exchange processes. "When we speak about the appearance of life on our planet, we are actually referring to nothing other than the formation of its biosphere," Vernadsky wrote. He formulated several important biogeochemical principles, according to which the biogenic migration of atoms of the chemical elements in the biosphere increases during the process of creation of stable life-forms, as these strive to maximize their manifestation. The evolution of species proceeds in the same direction. Throughout geological time, from the Cryptozoic Eon[3] onward, the process of populating the planet was necessarily the maximum possible for living matter, and never in the course of all geological time has there been a geological epoch without life. It follows that modern living matter has a permanent genetic link with that of preceding geological epochs. Obviously, while there has been no fundamental change in the geochemical influence of living matter on its environment, this does not mean that there is no process of evolution.

He viewed the biogeochemical functions of the biosphere, which provide the basis for life, as immutable, having existed continuously throughout geological time. Vernadsky included among these biogeochemical functions: gas exchange involving N_2-O_2-CO_2-CH_4-H_2-NH_3-H_2S, which is effected by all organisms; the oxygen function performed by photosynthetic plants; the oxidation and reduction functions, supplied primarily by bacteria, including autotrophic bacteria; the calcium function, carried out by algae, moss, and marine organisms, as well as by bacteria; and the concentration function, performed by unicellular and multi-cellular organisms. Biogeochemical functions are also responsible for the breakdown of organic compounds by bacteria and fungi, and for metabolism and respiration.

Vernadsky considered the biogeochemical energy of living matter to be based, above all, on the multiplication of organisms, caused by "their unremitting endeavor (determined by the energetics of the planet), to achieve a minimum of free energy," in conformity with the fundamental laws of thermodynamics, which are consistent with the conditions required for the existence and stability of the planet.

As we said above, viewing life as a planetary phenomenon, and all living organisms as an inseparable, lawful part of the biosphere, Vernadsky believed that life determines the chemistry, migration, and differentiation of the chemical elements. He thought that living matter encompasses and regulates all, or nearly all, the chemical elements in the biosphere, and that microorganisms play the primary role in these processes. "These are the most powerful biogenic planetary geological force, the most powerful manifestation of living matter," he wrote. And further on: "Life consists to a significant extent of the extraction of particular chemical elements from the environment, their filtration through the compounds or fluids of the organism, and their redischarge into the environment, often in the form of new compounds." The atomic ratios between calcium/magnesium, potassium/sodium, and other combinations, are transformed in the biosphere by the biogenic migration of chemical elements, which is accomplished by living organisms according to their various needs for particular elements.

According to Vernadsky, living matter differentiates not only chemical elements, but also individual isotopes, as has been experimentally proven for highly volatile ones—oxygen, nitrogen, hydrogen, and sulfur. In so doing, organisms, as a rule, selectively absorb primarily the light isotopes of these elements. Investigating the chemical composition of living matter, he distinguished four groups of organisms by their ability to concentrate one element or another. He called the simultaneous presence of chemical elements in an organism and in the Earth's crust "*organogenic paragenesis*," because it was caused not by the chemical properties of the elements, but by the properties of the organisms. These paragenetic associations of elements, created by living matter, are inherited in a different form by the biogenic component of the Earth's crust.

Vernadsky paid a great deal of attention to the question of the source of life's appearance on Earth. The theory that living beings originated from inorganic matter (abiogenesis) contradicted biogenesis, the theory of the "eternity of life," which is based on the principle *omne vivum ex vivo*, that is, that life arises only from life. This principle was established empirically in 1668 by the Italian scientist Francesco Redi, who demonstrated that fly larvae only develop in rotten meat when it contains eggs laid by flies. This was confirmed in the 18th century by the Italian scientist Lazzaro Spallanzani, who showed that microorganisms cannot develop in boiled broth. The decisive proof was provided in 1861 by the French scientist Louis Pasteur, whose experiments, like Redi's principle itself, did not deny, generally speaking, the possibility of abiogenesis in earlier geological periods as a special form acquired by matter at a certain stage of its development, but only indicated the limits within which abiogenesis does not occur. Nor did they contradict the cosmogenic hypothesis of the origin of life (panspermia), put forward at the end of the 19th century by Svante Arrhenius.

Vernadsky originally highly esteemed Redi's princi-

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[3] The Cryptozoic Eon is a now mostly obsolete synonym of the Precambrian Era.

ple, while later also conducting an in-depth study of the question of abiogenesis. He thought that notions about the beginning of life on Earth that were not connected with the planet's geological structure and history ran counter to accurate knowledge. This applied both to the possibility of the introduction of living matter to our planet from space, and to the possibility of life's having formed out of inert matter in a geologically ancient period of the Earth's history, through "spontaneous generation"—abiogenesis of one form or another, when natural conditions were radically different from today's. In the first case, one could assume that "life is just as much an eternal feature of the structure of the Universe, as are the atom and its aggregates" (and so the process may be ongoing even now), and that the conditions for life's origin in outer space involve processes not occurring on Earth, but that living organisms, when they fell to Earth, found favorable conditions here and were able to establish themselves. The second case assumes that there were physicochemical phenomena, conditions, and states on the surface of the young Earth that were conducive to and necessary for abiogenesis. The first primitive organisms to appear probably made use of basic organic substances such as monomers from non-biological sources, similar to what is occurring today in the Earth's deep biosphere.

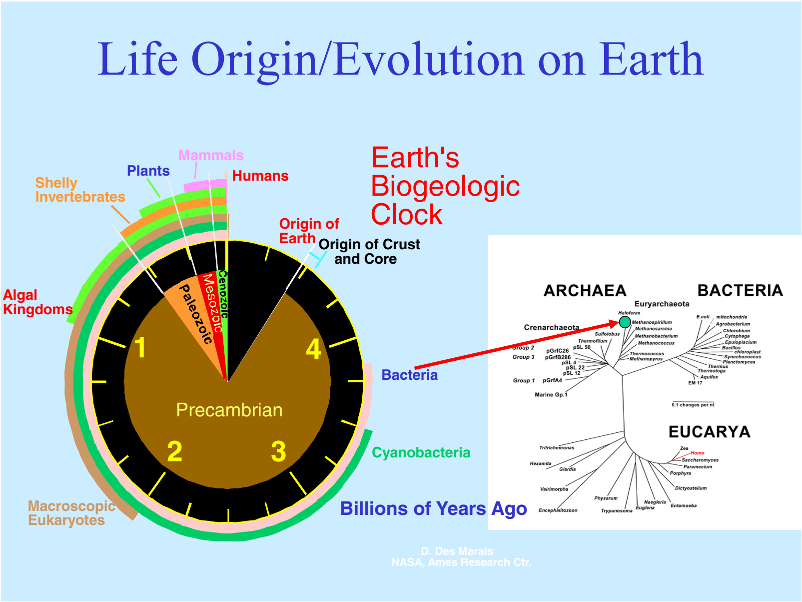
Vernadsky's conception was that, already in the early Archean, millions of open systems could have emerged on the basis of diverse primordial high-molecular-weight protein and nucleotide compounds. These systems would have been capable of remaining in a state of dynamic equilibrium for a certain time. The high degree of internal organization of some of these systems led to the appearance and persistence of metabolic processes and primitive replication, which served as the foundation of the incipient biosphere. The formation of the biosphere, in turn, launched the process of evolution and the creation of "morphologically different hereditary lines," in such a way that "the evolutionary process, in whichever of its forms we may consider, always occurs within the biosphere, that is, within living nature, and there can be no changes of the form of organisms outside of living nature." The physicochemical state of the biosphere, and its appearance, change in very close connection with the evolution of living forms: in the Precambrian, calcareous algae appeared; in the Cambrian, skeletal organisms; and in the Anthropogenic Era, man. The evolution of species becomes the evolution of the biosphere, while the geochemical energy of organisms should be seen as the effect of the action of a given species on its environment.

Studying the peculiarities of the space occupied by life, Vernadsky devoted much attention to the problem of dissymmetry, which, in contrast to classical symmetry, is characterized by the preponderance of left-handed or right-handed enantiomers. This phenomenon, which was discovered by Louis Pasteur and substantiated by Pierre Curie, is exclusively the property of living organisms and is absent in non-living nature. It was discovered that compounds concentrated in an egg or seed rotate the plane of polarization of light in a particular direction and such orientation is also present during crystallization of these compounds, as well as in organisms' ingestion of similarly oriented enantiomers and avoidance of different ones. Vernadsky regarded dissymmetry as a powerful factor in the selectivity and stability of life and thought that its genesis from inert matter, abiogenesis, could occur only in the peculiar environment of Earth, without cosmic factors playing a role. Vernadsky maintained that by studying this phenomenon, we penetrate more deeply, and in a new way, into the properties of the world around us than physics does. This fundamental property of life, the unidirectionality of biological molecules (left-handed L-amino acids and right-handed D-sugars), is now known as *chirality*.

In his discussions of the origin of life and the initial stages of the biosphere, Vernadsky above all strove to explain the markedly heterogeneous structure of the space of the biosphere, the profound physical distinction between the parts of the biosphere occupied by living organisms and the parts occupied by inert matter. On the basis of this conception, he ruled out the possibility of life's originating under isolated conditions such as, in particular, local processes of abiogenesis or the transmission to Earth of morphologically uniform organisms (for example, bacteria or algae) from which the millions of species of plants and animals would have emerged in the subsequent process of evolution. In his opinion, "a complex set of life forms must have appeared simultaneously, and then developed into today's living nature." Let us note that in his early works, Vernadsky expressed doubt that "all the diversity of organisms and complex living matter could have evolved from a few unicellular organisms that had settled on the Earth's surface from outer space." Later, however, he did not exclude the possibility of a cosmogenic origin of living matter, with its primitive forms having been brought to Earth in the very earliest stage of the planet's evolution. We find reference to this in the following statement: "The ability of unicellular organisms to perform in full all the geochemical functions of organisms in the biosphere makes it probable that they were the first appearance of life. For we now can trace the evolutionary creation of more complex organisms from simpler ancestors." It should be emphasized, once again, that this is a manifestation of the organized state of the biosphere through its biogeochemical functions.

At the same time, Vernadsky talked about directionality as a characteristic feature of the evolutionary process of

Figure 3



The evolution of life on Earth ("The biological clock of the Earth").

Source: D. Des Martis, NASA Ames Research Center.

life in the biosphere, which "is most intimately connected with the fundamental distinction between living matter and inert matter, and corresponds to the absolutely unique appearance in the biosphere of the energetic effect of the progress of life through time." Here we may note a direct link with thermodynamic irreversibility and Prigogine's notion of "the arrow of time."

There is still no consensus as to when and how life appeared on the young Earth. Vernadsky proceeded from the idea that the initial zones of life, and the biosphere, arose in the earliest geological epoch, that pre-biological evolution occurred very rapidly, and that the "field of life" has remained on the whole unchanged since the Archean Eon, as is indicated by the character and the paragenesis of the minerals forming the biosphere. Obviously this earliest stage of the biosphere included the abiogenetic synthesis of organic compounds and the matrix synthesis of macromolecules, followed by formation of the properties of metabolism, the mechanism of replication, and eventually the development of prokaryotes. Vernadsky considered as completely lawful the abiogenetic appearance of diverse life forms from inorganic substances, represented by the totality of many species, belonging morphologically to various sharply divided classes of organisms. This means that biocenoses must have developed immediately, although the subsequent evolutionary process was prolonged.

A number of investigators, following Vernadsky, think that the most primitive organisms, the eobionts, appeared on Earth 4.25 billion years ago, and that the emergence of photosynthesis in the prokaryotic protobionts dates from 3.5 to 4 billion years ago. This implies that the biosphere, populated by the eobionts, may have formed around 4 billion years ago and that the Earth's features took shape through an evolutionary process over the subsequent billions of years, in which life had emerged, and the biogenic migration of atoms played a decisive role (see Fig. 3).

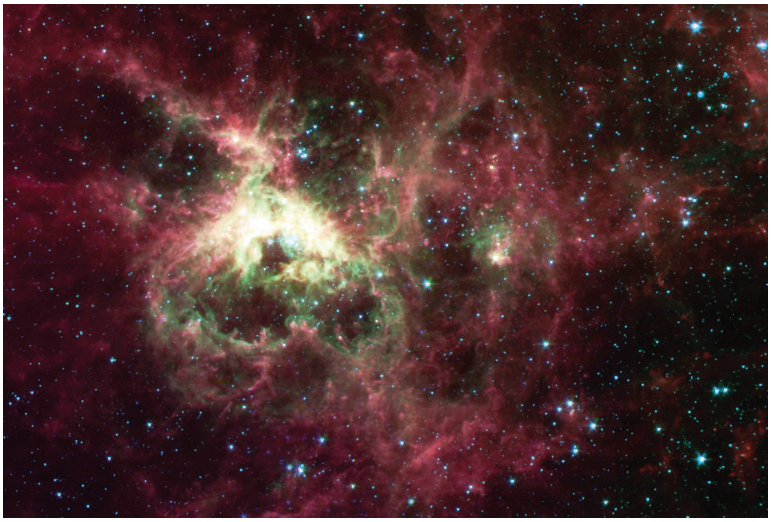
Thus a geochemical approach to the study of life gives us a better understanding of the peculiarities of its emergence and the way in which organisms act on their environment, as well as allowing us to formulate the conditions necessary for life to appear. This, in turn, imposes limits upon our conceptual models of forms in which either abiogenesis or the introduction of life from outer space might have occurred. In any case, the structure and properties of the space occupied by life (the biosphere, as distinct from other geospheres) had to have changed, and diverse special biogeochemical functions must have appeared. The latter were brought about by living organisms and are the functions of a single, indivisible set of organisms, a set comprised of the numerous morphologically diverse forms that cause the complexity of life.

The Connection with Astrobiology

V.I. Vernadsky's fundamental ideas about the biosphere and its indissoluble connection with the origin and evolution of life have remained fully relevant as decades pass. Impressive results have been achieved in the approach to the most difficult problem, the origin of life. At the same time, it has been realized that the phenomenon of life itself cannot be viewed in isolation, without reference to numerous factors that exist in the Cosmos; this has reinforced Vernadsky's concept of the evolution of the Earth as a combination of cosmic, geological, and biogenic processes. This is how astrobiology came into being, first of all as a framework for the attempt to uncover these relationships and to understand the phenomenon of life and how it arose on our planet, and then also to detect signs of life in the Solar System and beyond.

The chemical evolution of matter in outer space, which is the subject of astrochemistry, is an important aspect of the origin of life. Organic synthesis, a process that takes no more than a thousand years, occurs in the interstellar medium. Synthesis is particularly efficient in interstellar molecular clouds of gas and dust (Fig. 4), where it is fostered by the turbulence and evaporation of particles in the cloud. More than 200 fairly complex organic molecules have been found in molecular clouds, including a large quantity of hydrocarbons (building blocks of the polycyclic aromatic hydrocarbons, PAH), the simplest of which is benzene. About 70 amino acids were discovered in the Murchison and Murray meteorites, a finding which supports models of the extraterrestrial origin of the precursors of biomolecules.

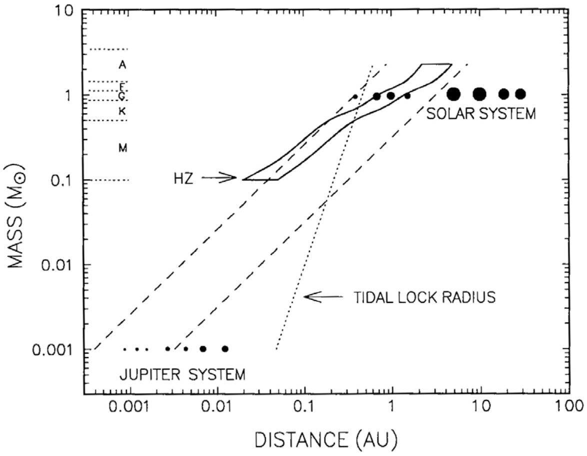
Figure 4



An example of a molecular cloud (Tarantula Nebula), in which star formation occurs.

Source: NASA, Spitzer Space Telescope

Figure 5



A habitable zone for planets in the vicinity of a mother star (the distribution of the sphere of the habitable zone). The vertical axis indicates the spectral class and the mass of the star relative to the mass of the Sun. The horizontal axis gives distance in astronomical units. The dashed lines show the boundary limits for the planets depending upon the star class and the radial distance, and the dotted line shows the tidal lock radius. Theoretically, three planets of our Solar System exist within the boundary of the habitable zone: Earth, Venus, and Mars.

Source: J.F. Kasting, D.P. Whitmire, R.T. Reynolds. "Habitable Zones Around Main Sequence Stars" *Icarus* **101**:108-128 (1993)

In discussing the origin of and search for life, the biological mechanism of life on Earth is naturally our primary point of reference. Of course, the natural conditions on the planet that were necessary for prebiotic evolution and the origin of life are of paramount importance, and Vernadsky paid them special attention. Life as we know it can exist only in a very limited range of natural conditions. In other words, from the outset there are fairly strict limitations on the mechanical and thermodynamic parameters of a celestial body on which life might come into being. A planet suitable for habitation must meet well-defined criteria, including size and mass, since a large planet accretes material until it becomes a gas giant, while a small planet loses its atmosphere; temperature and pressure allowing for the presence of liquid water; the existence of an atmosphere with a suitable chemical composition, excluding aggressive impurities; a radial distance from the parent star that makes favorable climatic conditions possible; and an optimal distance from the parent star, because a planet that is too close is locked in tidal resonance not favorable for the development of life (Fig. 5). Meanwhile, based on our terrestrial experience, we should also keep in mind a number of favorable circumstances for the origin, support, proliferation and detection of life. Indeed, with respect to metabolism (respiration, alimentation) life has great variety and adaptability, and living organisms are able to withstand extremely harsh environmental conditions (a wide range of temperatures, low pH), and the ingredients necessary for life are widely distributed (see Figs. 6,7). It is no accident that Vernadsky, based on what was known in his day, supposed that life might exist on Venus, Mars, and even Jupiter and Saturn.

Now we know that in the Solar System, the habitable zone, within which a planet could theoretically support a climate favorable to the emergence and continued existence of life, is near Earth's orbit, coming far short of

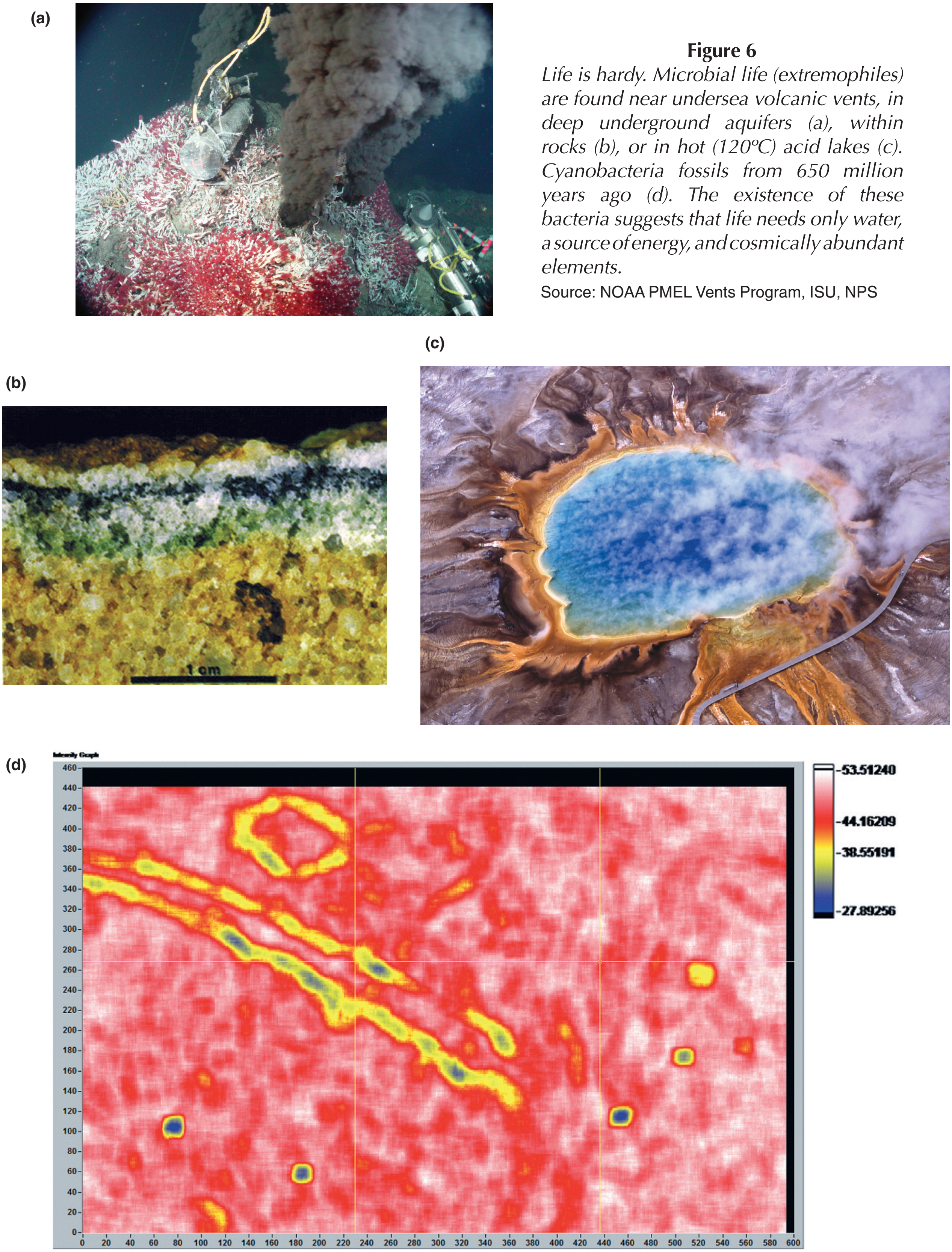
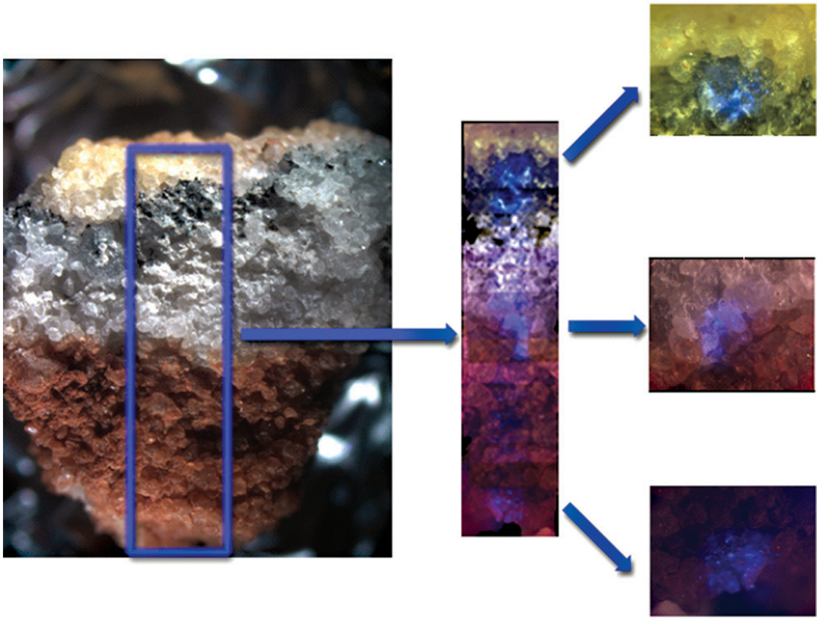


Figure 6

Life is hardy. Microbial life (extremophiles) are found near undersea volcanic vents, in deep underground aquifers (a), within rocks (b), or in hot (120ºC) acid lakes (c). Cyanobacteria fossils from 650 million years ago (d). The existence of these bacteria suggests that life needs only water, a source of energy, and cosmically abundant elements.

Source: NOAA PMEL Vents Program, ISU, NPS

Figure 7



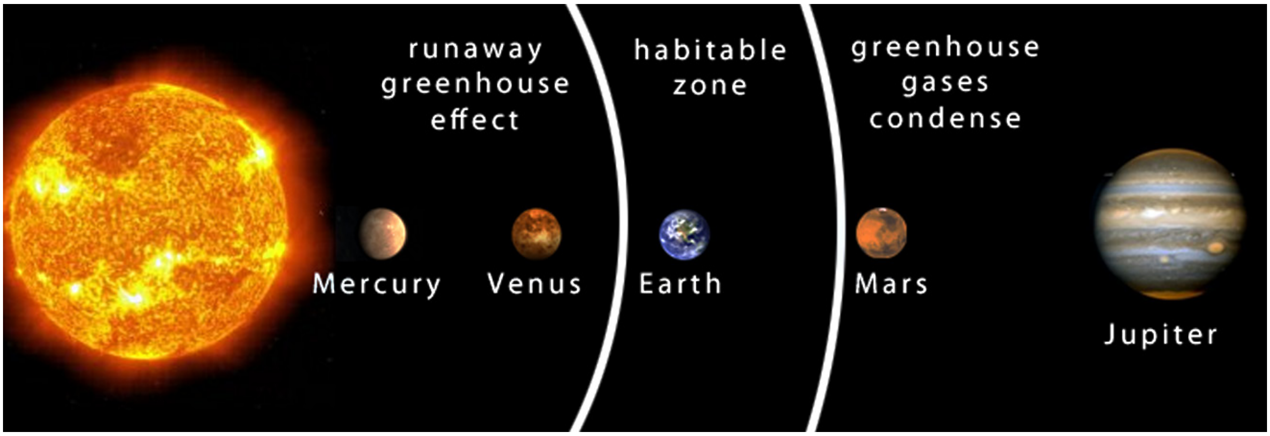
Antarctic dry valley cryptoendolithic community, visible light and deep UV (224 nm) images.

Source: Center for Life Detection, JPL/CIT

the orbit of Venus, and only approaching the orbit of Mars (Fig. 8). Unfortunately, we cannot yet answer the question of what distinguished Earth from the other planets in the Solar System, making the emergence of the biosphere possible here. On Venus (Fig. 9), this possibility is excluded by the runaway greenhouse effect, which has raised its surface temperature to 475° C and its pressure to 90 atmospheres. At the same time, there is reason to believe that in the early Noachian Era favorable climatic conditions for life to arise existed on Mars, including quite deep water oceans. The climate changed catastrophically about 3.6 billion years ago, leaving a waterless desert surface and a rarefied atmosphere (Fig. 10), but traces of primitive Martian life may have survived. It is not impossible that life may exist in what are assumed to be oceans of water under the icy surface of two of the Galilean moons of Jupiter, Europa and Ganymede (Fig. 11). The evolution of organic material on Titan, a satellite of Saturn (Fig. 12) is a question of great interest. Recently, researchers' attention has been increasingly attracted to exoplanets, especially the Earth-like planets that have already been discovered in orbit around other stars, and also to the prospect of finding life on them, the more so since the impact of life on the environment is rather noticeable and lends itself to external observation.

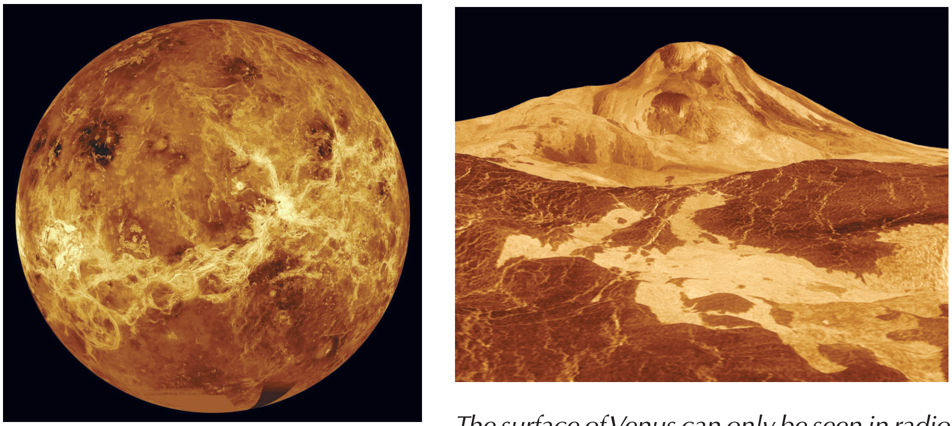
Among the astronomical aspects of the origin of life, the connection of the biochemical evolution of matter with cosmic factors merits attention. As discussed above, Vernadsky repeatedly turned to the choice between alternative models of the origin of life and the biosphere: directly on Earth, or with an external cosmogenic source

Figure 8



The actual habitable zone in the vicinity of Earth.

Figure 9
Images of Venus



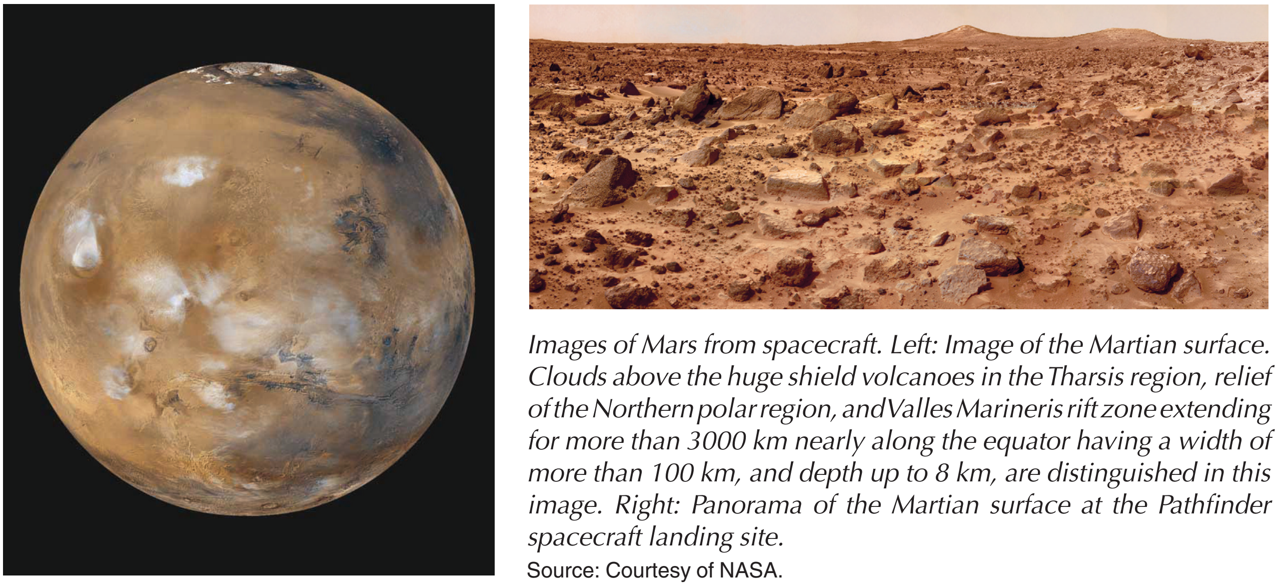
The surface of Venus can only be seen in radio wavelengths, which are transparent to the thick atmosphere and clouds. Radio mapping has revealed many relief features and peculiarities of the Venusian surface. Left: Mosaic of images of the surface returned by the Magellan spacecraft; more or less ordered structures can be distinguished in the chaotic pattern of the relief. Right: Evidence of volcanic activity. An image of the surface outpouring of volcanic lava ("pancakes") in perspective projection from the radar mapping of Venus from the Magellan spacecraft.

Source: Courtesy of NASA.

playing a part. Our modern understanding of the important role of matter transport and of migration and collision processes in the Solar System, in which the key role is played by comets and asteroids with a carbonaceous chondrite composition, allows us to consider these small bodies as likely carriers of prebiotic or even biotic matter from the primary asteroid belt and from the trans-Neptunian Kuiper Belt (Fig. 13). Carbonaceous chondrites are the key to finding extraterrestrial sources of organic matter: they contain chemically bound water and their parent bodies (hydrosilicates) were probably formed in water. Comets enriched with water and carbon are even more prolific carriers of the seeds of life. Indeed, the ratio between the carbon in comets and the carbon in carbonaceous chondrites is 10:1, although the meteorites' volatile organics might have been lost at later stages during asteroid impacts. Given the key role of water in the origin of life, it is important to note that modeling has indicated that the Earth could have received a large influx of volatile matter from comet and asteroid bombardment, including a quantity of water comparable to the volume of our planet's oceans.

Of course, the question of how life originated is of

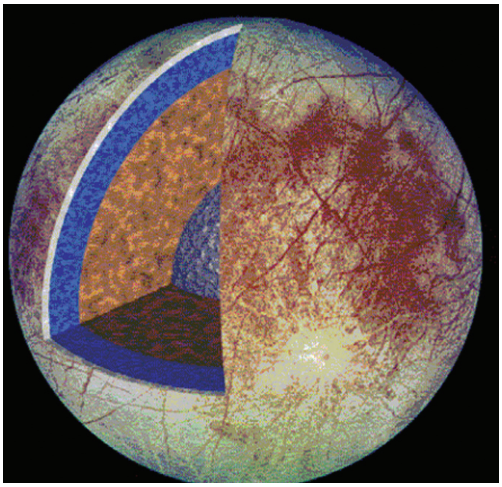
Figure 10

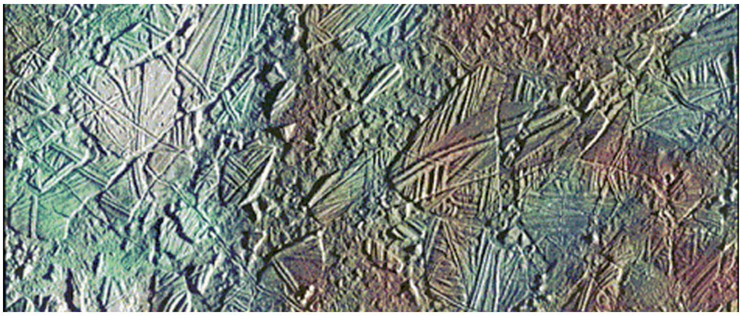


Images of Mars from spacecraft. Left: Image of the Martian surface. Clouds above the huge shield volcanoes in the Tharsis region, relief of the Northern polar region, and Valles Marineris rift zone extending for more than 3000 km nearly along the equator having a width of more than 100 km, and depth up to 8 km, are distinguished in this image. Right: Panorama of the Martian surface at the Pathfinder spacecraft landing site.

Source: Courtesy of NASA.

Figure 11





Left: Jupiter's Galilean satellite Europa. The surface is crisscrossed by ridges, troughs, and faults whose relief does not exceed several hundred meters in height. The absence of craters is indicative of a young surface. The present-day model of Europa's internal structure assumes there is a water ocean ~50 -100 km in depth under a relatively thin ice crust ~10 -15 km in thickness and a silicate mantle and a core composed of rocks lie below it. Right: A 70 km x 30 km area of Europa's surface (the Conamara region). The colors are enhanced to emphasize the relief features; the Sun is on the right. The white and blue regions correspond to a fresh surface partially covered with dust, while the brown ones probably owe their origin to mineral deposits. The areas ~10 km in size bear the traces of displacements of the upper ice crust layer, which can be associated with the presence of water or soft ice at a comparatively small depth.

Source: Images from Galileo spacecraft, courtesy of NASA.

paramount interest. When we talk about the origin of life, we are dealing not only with the formation of chains of nucleotides and amino acids (nucleic acids and peptides), which constitute the informational (DNA and RNA)[4] and the functional (proteins) basis of life, respectively, but also with the formation of the first ecosystem. Among the various conceptual approaches to the origin of life, the most noteworthy and well-founded, in our view, are the hypotheses of an ancient RNA world and of a sequential ordering process, developed by the author's colleagues A.S. Spirin and E.M. Galimov, respectively. In each of these, processes of biochemical evolution are crucial. As for Darwinism, it has an important role with regard to the stages of biological evolution, but not at the early stages of life's coming into being and the development of the molecular mechanisms of biological systems. From this perspective, molecular

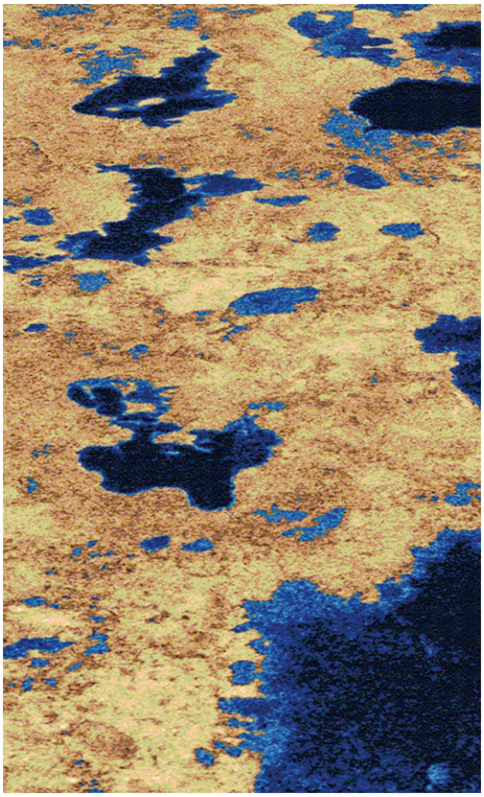


Figure 12

The surface of Saturn's satellite Titan. The dark spots on the lighter surface composed of water and hydrocarbon ices are associated with methane lakes, which corroborates the hypothesis about the existence of a methane cycle between the surface and the atmosphere.

Source: Images from the Huygens lander, courtesy of ESA.

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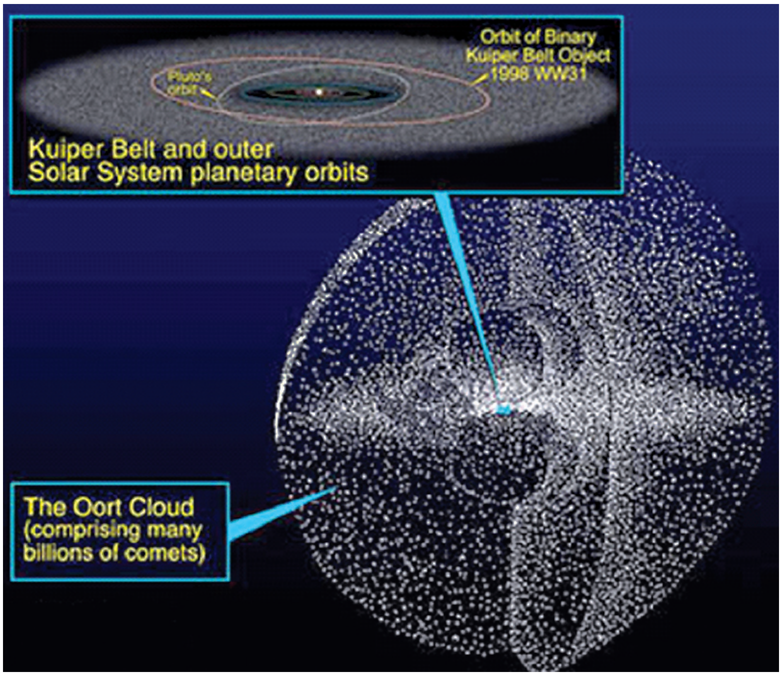
[4] We note that only about 5% of the double DNA spiral is used for coding, while the remainder contains information on how the sequence of genes is to be ordered.

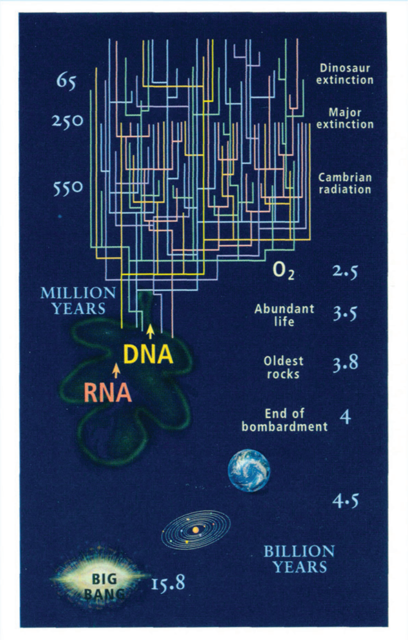
Figure 13

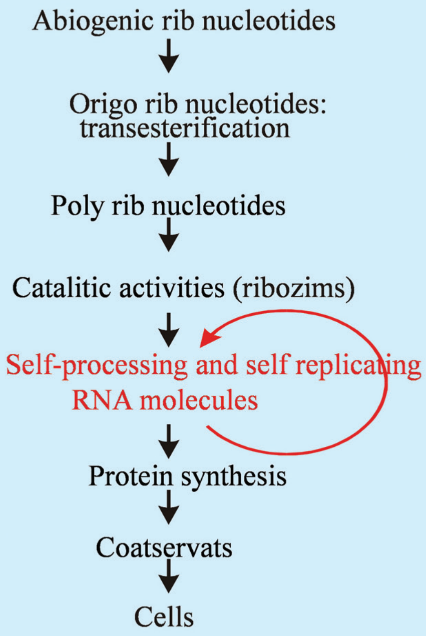


Left: The Oort cloud and the Kuiper Belt. The Kuiper Belt located at the outskirts of our planetary system (40-100 AU) lies deep inside the Oort cloud whose outer boundary is at a distance of 104 – 105 AU. Right: Image of Hale-Bopp comet during its encounter with the Sun. A small nucleus (~10 km) is hidden deep inside a bright region, the coma (cometary atmosphere) tens of thousands of kilometers across produced by the sublimation of gas and dust from the icy surface of the nucleus. Extended type I and II tails are clearly seen.

Source: NASA

Ancient RNA world as the precursor of life origin on Earth





Abiogenic rib nucleotides

Origo rib nucleotides: transesterification

Poly rib nucleotides

Catalitic activities (ribozims)

Self-processing and self replicating RNA molecules

Protein synthesis

Coatservats

Cells

Figure 14

Left: A chronology of events in the course of the evolution of the biosphere. Right: A schematic depiction of the evolution of life from its origin in the ancient RNA world.

Source: J.F. Atkins and R.F. Gesteland; A.S. Spirin.

genetics, biochemistry, and Darwinism are complementary, and constitute the foundation of modern evolutionary theory.

An Ancient RNA World

Among the arguments in favor of the concept of an ancient RNA world, as the basis for the evolution of the primal biosphere, are the unique properties of the RNA molecule (a three-dimensional heteropolymer) defined by the sequences of RNA bases along the strands and the character of the coiling. Indeed, ensembles of RNA molecules carry out the functions of assimilation, metabolism, and replication. It is important to emphasize that RNA may contain genetic information or serve as a temporary copy of genetic information. For this purpose it uses a short-lived intermediate molecule (mRNA), which carries the initial information for production of a specific protein and copies the cell genome—DNA. Thus, RNA has the ability to perform many of the basic functions of DNA, participating in the ribosome's process of protein synthesis. These include encoding—programming the synthesis of biopolymers by a linear sequence of polynucleotides; replication—strict copying of genetic material; the self-folding of linear polynucleotides into unique compact configurations (3D structures); recognition—specific interaction with other macromolecules; and catalytic functions. To this list should be added the fact that an RNA molecule has transfer properties (tRNA); that is, it transports other molecules that are necessary for a number of biological reactions and for protein synthesis. Each of the 20 existing tRNA molecules can attach to only one of the 20 amino acids, which it transports to a certain ribosome and then integrates into the chain of protein being synthesized, in accordance with the specifications contained in the intermediate mRNA molecule.

Then there are catalytic RNA molecules (ribozymes), which are involved in protein synthesis, along with standard protein catalysts (enzymes). These ensure the selection of specific intermolecular reactions and reduce the amount of energy they require. In addition, ribozymes provide the correct arrangement of nucleotide bonds in the chain during splicing of the mRNA molecules; only after this will they be read correctly by the ribosome in protein synthesis. Thus ribosomal RNA molecules (rRNA) play a very important role in protein synthesis, because they form the structural core of the ribosome, consisting of more than 50 different proteins and several rRNA. The ribosome, in a sense, "relies on" the catalytic functions of the rRNA during protein synthesis, and by reading the information encoded in the mRNA, it "knows" which protein to make. However, the extremely complex mechanism by which the genetic information of nucleic acids is decoded into the structural parameters of proteins, and how this mechanism was formed in the process of evolution, is not yet fully understood.

It follows from what we have said here that RNA, as the working instrument of cellular production, could have been the prototype of living systems. However, the emergence of an RNA world and its evolution up to the point of the first highly organized organisms—bacteria—over an extremely short period of time (about the first half-billion years in the Earth's history) is unlikely, as advocates of this concept themselves admit. This difficulty may be eliminated by adducing a hypothesis that ensembles of RNA molecules originated and underwent their initial evolution in the environment of outer space, especially on small bodies such as comets, which bombarded the Earth and other planets intensively about 4 billion years ago. Therefore the idea of an ancient RNA world is linked with the possibility of the extraterrestrial origin of life.

A Sequential Ordering

An alternative to the conception of an ancient RNA world is that of a sequential ordering of the processes of the origin and early evolution of living matter as the chemical basis of life. This approach is consonant with Vernadsky's ideas about processes of abiogenesis in open systems that have a high degree of internal organization and are capable of remaining in a state of dynamic equilibrium for some time, and about the organized nature of the biosphere, based on the biogenic cycles of the atoms of chemical elements, which preclude a chaotic state. As part of this concept, in which the basic functions of RNA molecules also play an important role, as mentioned above, the origin of life is conceived of as a continuous ordering process in an open stationary system, which, in contrast to a conservative (Hamiltonian) system, which conserves energy, is a dissipative system that exchanges energy with the environment. Such a system would consist of prebiotic organic compounds that had emerged in the process of chemical evolution, possibly having originated in outer space. Conjugated chemical reactions occur in the system, producing not only positive but also negative entropy, which is a necessary condition for structural organization (ordering) in a chaotic environment. The energy is thereby maintained above a certain minimum level, as long as Prigogine's minimum entropy production conditions are met.

Chemical ordering (limitation of the number of partners in a reaction, and the number of mechanisms and interaction paths) is implemented efficiently by selective catalysis employing biochemical catalysts—enzymes, which are peptide chains (proteins) folded into three-dimensional structures; these are highly active and they efficiently accomplish the ordering by means of selective catalysis. According to Galimov, the adenosine triphosphate (ATP) molecule, which consists of adenine, ribose, and a phosphate group, could play a key role in these processes. It absorbs solar energy and transfers it to the conjugated chemical system, and the universal mediator for coupling is water (hydrolysis). An appealing factor here is that ATP is synthesized from simple molecules, hydrogen cyanide (HCN) and formaldehyde (HCHO), which are widespread in outer space.

However, unlike Galimov, who assumes linear processes of increasing complexity in the above concept, the author believes that the accumulation of changes occurs in a highly nonlinear system, which leads to instability, bifurcations (discontinuities), and successive transformations of the system into a qualitatively new state. In mathematical language, such a process corresponds to the branching (qualitative change) of solutions under certain (critical) parameter values. For each new state (self-organization) of the system there is a different corresponding set of interactions of the molecular complexes. In other words, the increasing ordering of the original (chaotic) system takes the form of a sequence of bifurcations, from the appearance of primitive polymer structures and the development of the universal catalytic function of peptides, to the emergence of the nucleotide sequences involved in protein synthesis, and the genetic code in which the general plan of organism development as well as its numerous individual peculiarities are recorded.

From the standpoint of stochastic dynamics that we are developing, such events are nothing other than the outcome and consequence of local instability in a nonlinear chaotic dissipative system with many degrees of freedom, while the sequence of changes in state (evolution) of the system leads to self-organization. The sequential-ordering model furthermore requires, as an important property, that there be feedback for the transition to a new level of organization. A reducing medium is also required under conditions of the separate existence of an atmosphere and a hydrosphere, as well as the accessibility and mobility of phosphates, which generally is not inconsistent with current ideas about the natural conditions on Earth at the time of the appearance of the first primitive forms of life.

According to this concept, the capability of ordering through selective catalysis and the capability of self-reproduction are the two most important properties of bioorganic compounds, necessary for the origin and evolution of life. The initial ordering is created by nucleotide chains and amino acid chains (peptides). Chains of amino acids form the universal design of biological structures capable of infinite variety, and chains of nucleotides provide for self-reproduction (replication) as a fundamental property of living matter. In other words, between these two classes of organic compounds, nature has divided up: the tendency toward ordering through selective catalysis, and the capacity for self-reproduction.

It is of particular note that in the world of organic compounds, ordering is effected by the unique properties of carbon compounds. Only on the basis of carbon can complex biopolymer structures be created, and ordering through selective (enzymatic) catalysis and replication (self-reproduction) take place. This statement should be considered as the main paradigm of the origin of life. Therefore, the discussions sometimes encountered about the possibility of life existing on the basis of silicon, for example, are groundless. If there is life in the Universe, its molecular construction is probably analogous to that of life on Earth—that is, based on carbon and its compounds, and on principles that allow a protein-nucleotide form of functioning.

Evolution

We shall now briefly touch upon the issue of biological evolution. The formation of biopolymers capable of catalysis and replication includes the appearance of an intermediary between peptides and nucleotides, such as the above-mentioned transfer RNA (tRNA); it also includes the formation of the genetic code. The emergence of the genetic code completes the stage of prebiotic evolution, and biological evolution itself begins (the evolution of life). As we said above, Vernadsky reasonably thought that one of its fundamental properties was dissymmetry, or chirality.

Biological evolution is understood as cumulative changes over time. Through a continuously increasing state of order (including RNA precursors), one believes that the first living organisms appeared on Earth approximately 3.8 billion years ago. These were bacteria with complex molecular apparatuses for heredity, protein synthesis, energy supply, and metabolism. The emergence of the first living systems (prokaryotes, eukaryotes) was accompanied by evolution on the level of cells,[5] organisms, and ecosystems, and the formation of what Vernadsky saw as the biosphere. As this occurred, the ordering processes were inevitably accompanied by processes of disorder and chaos. In the competitive processes of ordering/disordering (degradation), Darwinian natural selection played a decisive role.[6] Thus we emphasize again the important role of Darwinism in biological evolution, but not at the early stages of the establishment of life and the development of the molecular

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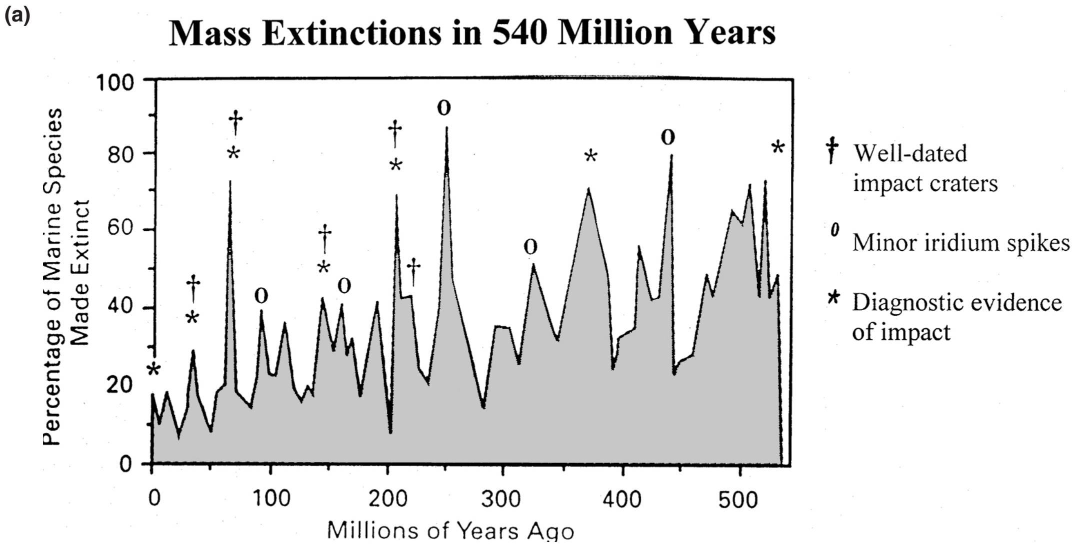
5. Here we should emphasize again the striking self-organization of living species on the cellular level involving a well-controlled and coherent sequence mechanism of turning on and off specific groups of genes in the different cells.

6. It is worth noting that natural selection is responsible for the elimination of the dominant part of mutations harmful to life; their carriers fail to survive or leave behind posterity.



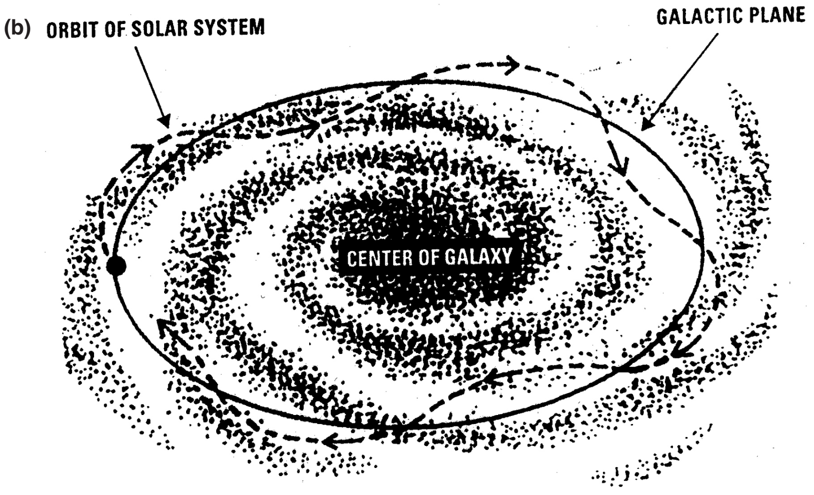


Figure 15

Above: The mass extinctions of living organisms on Earth during the last 540 million years. The events correspond to impact craters, enriched with iridium and containing other signs of falling cosmic bodies. Right: Schematic view of the movement of the Solar System through our galaxy.

self-organization mechanisms of biological systems. We emphasize once again that from this perspective, molecular biology, biochemical genetics, and Darwinism are not contradictory, but rather complementary and quite coherent foundations of modern evolutionary theory. Darwinism may be further developed through the concept of "covariant reduplication," proposed by the highly regarded Russian scientist N.V. Timofeyev-Resovsky,[7] which is based on the idea of matrix reproduction and replication of different variants of genetic texts, including those which have undergone mutation, followed by these versions being "offered" to nature to choose from. This concept is closely related to Vernadsky's ideas, discussed above, about the matrix synthesis of organic macromolecules during the evolution of the biosphere. Accordingly, the matrix mechanism of variation and heredity is associated with natural selection and the theory of evolution.

The Connection to Philosophy

We encounter highly relevant philosophical considerations in Vernadsky's manifold scientific legacy. Here we shall briefly touch upon only a few issues that are directly related to his scientific conceptions of the biosphere and the origin of life, while they also extend to pressing global problems for mankind.

A distinctive feature of all his creative work was his ability to see beyond the particular to the general, and, by analyzing actual data, to arrive at philosophical conclusions and generalizations, although he considered himself a philosophical skeptic. The basis for this view was his conviction that "no single philosophical system... is capable of achieving that general validity which science achieves (and only in some specific instances)."

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[7] Also written "Timofeev-Ressovsky."

He was critical of all philosophical systems, always adhering to his chief postulate: "All scientific work rests on the foundation of a uniform axiomatic assumption that the object of scientific study is real—that the Universe is real and it is lawful; that is, that it can be comprehended by scientific thought." He considered only the scientific outlook to be "an expression of the human spirit," while acknowledging that science is to some extent nourished by ideas and concepts which originate in the domain of religion and philosophy. In his article "On the Scientific World Outlook," he wrote that "the boundary between philosophy and science with regard to the objects of their investigation disappears, when it comes to general questions of natural science." Moreover, it is possible to formulate general laws of development of a scientific outlook only in the context of the historical process, taking into consideration the stages of advancement of scientific knowledge, and in interrelationship with other sciences and with the social conditions of various historical periods.

Understanding life as a function of a lawful geochemical mechanism in the biosphere, Vernadsky believed that biology, together with physics and astronomy, would provide deep insight into the foundations of the Universe. Remaining faithful to an empirical approach in his study of natural phenomena, yet rendering theoretical investigations their due, he rejected the views of Pierre-Simon LaPlace, who had asserted that a single formula could describe "everything that takes place in the natural order." Vernadsky thought there were "no grounds for thinking that, with the further development of science, all phenomena capable of scientific explanation would be subsumed under mathematical formulae or under some expression of numerical correlations." In his writings, Vernadsky preferred to use the term "living matter" rather than "life," seeing the former as part of the Earth and of the Cosmos, whereas he considered the concept of "life" to be incomparably broader, extending to philosophy, folklore, religion, and artistic creativity. Basically, he resolutely counterposed his own scientific conception to commonly held philosophical views or religious beliefs. Vernadsky complained that "philosophical thought has turned out to be powerless to compensate for the spiritual unity connecting humanity" and that philosophy lagged behind "the demands of the natural sciences." At the same time, he cherished the humanist idea of the unity of man and the Universe, and we must therefore include him in the ranks of scientists, writers, and philosophers who are outstanding representatives of Russian cosmism, the most noted being space pioneer Konstantin Tsiolkovsky.

Vernadsky had a thesis that became well-known: "Mankind, taken as a whole, is becoming a powerful geological force. And the question is arising before mankind, before man's thoughts and works, of reconstructing the biosphere in the interests of free-thinking humanity as a unified whole." Two very important circumstances underlie this thesis. The first is the understanding, as we have indicated, that life is a planetary phenomenon and that "living matter encompasses and regulates all, or nearly all, the chemical elements in the biosphere." Secondly, humanity stands as one before nature, and therefore no problems of the biosphere have a narrow, national character. "We must not," Vernadsky wrote, "act with impunity against the principle of the unity of all people as a law of nature." We see in this statement the position of a humanist scientist with a deep sense of responsibility for the fate of our planet and concern about an uncontrolled attitude toward global environmental problems, an issue that has now become particularly acute.

Observing the transformation of mankind's economic activity into a powerful factor in the evolution of the biosphere, Vernadsky was very far from thinking that scientific and technological progress should be halted, or that the advance of civilization should be slowed down, much less terminated; he simply called for the rational management of natural resources. "For the first time," he said, "man's life and his culture encompass the entire upper envelope of the planet—in general, the entire biosphere, the entire domain of the planet connected to life. We are present at and vigorously participating in the creation of a new geological factor in the biosphere, a factor of unprecedented power and universality. ... Man has actually comprehended for the first time, that he is an inhabitant of the planet and may—must—think and act with a new perspective, not solely with the perspective of a single individual, family, or clan, or of nations or alliances among them, but with a planetary perspective."

These considerations led Vernadsky to the concept of the noösphere (from the Greek word for reason, noös), as a new phase in the evolution of the biosphere. He provided this term, which had been coined in 1927 by the French scientists Eduard Le Roy and Pierre Teilhard de Chardin, with a much deeper significance, discarding, in particular, the mystical connotation which de Chardin, a fervent Catholic, had given to it. Using this concept, Vernadsky developed his own body of work on the biosphere and the inevitability of its transformation into the noösphere. In this new conception, he attributed paramount significance to scientific thought as a planetary phenomenon. Since the scale of human activity, superimposed on natural processes and foreign to them, continually increases and is becoming equivalent to the scale of natural geological phenomena, the evolutionary appearance of man and the development of scientific thought had to become natural processes, like everything else in the surrounding world. Consequently, man's scientific thought must develop according to the laws of nature, and not in conflict with them, striving towards the transformation of natural conditions in the direction of the maximum satisfaction of the material, energy, and aesthetic needs of mankind.

Understanding that "the face of the planet—the biosphere—is being radically changed chemically by man, both deliberately and, chiefly, unconsciously," Vernadsky called for these changes to be deliberately guided by human thought, for only then would the biosphere be transformed into the noösphere, as is necessary for mankind to flourish. Vernadsky understood that this transformation required that each individual take responsibility, and that the efforts of all peoples be joined to solve global problems, by strengthening political and other ties among nations, expanding the limits of the biosphere and stepping out into space, and discovering new sources of energy. He placed particular emphasis on the creation of conditions favorable to the development of free scientific thought, the rational transformation of nature, the prevention of war, and the elimination of poverty and hunger as the Earth's population increases. Here, he allotted an important role to science, being embraced to an ever greater degree in public life, "for science, in point of fact, is profoundly democratic; in it there is 'neither Jew nor Gentile,' " and its significance in the noösphere will continuously grow. This, his forecast, resounds strongly in our age of tremendous progress in science and technology, specifically, through the great breakthroughs in informatics and space technologies which have tightly connected the whole world through the internet and through efficient jet transportation.

"We are undergoing not a crisis, which perturbs the faint of heart," Vernadsky said, "but the greatest watershed in mankind's scientific thought, such as happens only once in a millennium; we are experiencing scientific achievements, the equal of which many generations of our ancestors never saw. Standing at this watershed, surveying the future that is opening up before us, we should be happy that we were destined to experience this, and to take part in the creation of such a future." This was the stand taken in life by the eminent scientist, thinker, and humanist Vladimir Ivanovich Vernadsky, the 150th anniversary of whose birth is being widely celebrated throughout the world today.

References

The article draws on original works of V.I. Vernadsky, which are cited in the text; the monograph Nauchnaya mysl kak planetnoye yavleniye [Scientific Thought as a Planetary Phenomenon] (Moscow: Nauka, 1991); as well as selected works published in the collection Vladimir Vernadsky. Otkrytiya i sudby [Vladimir Vernadsky. Discoveries and Destinies] (Moscow: Sovremennik, 1993); Nauchnoe i sotsialnoye znacheniye deyatelnosti V.I. Vernadskogo [The Scientific and Social Significance of the Activities of V.I. Vernadsky] (Leningrad: Nauka, 1989); V.I. Vernadsky i sovremennost [V.I. Vernadsky and the Contemporary World] (Moscow: Nauka, 1986).

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