Section Two

LIVING MATTER

Discovery of the Cold World on the Earth and in the Universe: from Ancient Natural Philosophy to Cryosophy¹

Vladimir Melnikov

Doctor Sci. (Geology & Mineralogy), Full Member of the Russian Academy of Sciences,
Tyumen State University; Institute of the Earth Cryosphere SB RAS (Tyumen, Russia)

E-mail: melnikov@ikz.ru

<https://orcid.org/0000-0002-0863-592X>

Roman Fedorov

Candidate Sci. (Philosophy), Institute of the Earth Cryosphere SB RAS; Tyumen State
University (Tyumen, Russia)

E-mail: r_fedorov@mail.ru

<https://orcid.org/0000-0002-3658-746X>

Discovering today diversity of extraterrestrial cryogenic objects, as well as the large range of scales and rates of cryogenic processes, undermines the conventional views of cold in the classical terms. The classical approach of natural sciences that study different cryogenic objects and processes separately is giving way to the apprehension of the cold world as a self-evolving complex system, with a great variability of its constituents in the scale of the Universe. In this respect, we discuss the methods and conceptual basis of the terrestrial and extraterrestrial cryology in terms of a new science called cryosophy. Cryosophy studies the role of cold in the origin and evolution of life and heat-mass interactions in the world. It addresses the key features and principles of the evolution of the cryosphere and uses both classical (for simple physical and chemical systems) and synergetic (for complex and living systems) approaches, as well as information logistic methods that generate knowledge about knowledge. Studies of cold date back to the ages of ancient Greek natural philosophy, which flourished between the 7th and 4th centuries BC. Unlike Greek natural philosophy, which pretended to be a universal

¹ The research is supported by the state assignment AAAA-A19-119071990006-3

© Melnikov, Vladimir, 2020

© Fedorov, Roman, 2020

syncretic science, cryosophy is a kind of integrator, which attracts different fields of knowledge related to the cold world and builds a framework for its ontology. The properties of ice can be summarized in a model of a multi-function system with six main components plotted in the scales of space (ice as a physical system and a natural material), energy (ice as a physicochemical system and a phase state), and time (ice as a system of information and control). The concept of cryodiversity covers multiple biotic and abiotic complex systems, such as cryophilic bacteria that live in permafrost, atmospheric precipitation, gas hydrates, etc. Cryodiversity also refers to cryogenic effects in the extraterrestrial space, which have been increasingly more widely investigated since the middle of 20th century. The evolution and properties of the cryosphere in different planets or other celestial bodies make part of the basic knowledge indispensable for the future exploration of the Universe.

Keywords: natural philosophy, cryosophy, cosmology, cold, cryodiversity, interdisciplinary researches, post-nonclassical science

Received: May 29, 2019; accepted: July 3, 2019

Philosophy and Cosmology, Volume 24, 2020: 48-60.

<https://doi.org/10.29202/phil-cosm/24/7>

Introduction

The science of geocryology that deals with objects, phenomena, and processes in the Earth's cryosphere originated about one hundred years ago. In its concepts and methods, it stemmed from geology and geography, while the object of studies was restricted to the lithosphere. However, the scope of subjects and methods of geocryology has expanded largely for its short history. In the 2000s, the lines of research encompassed the environment-forming role of permafrost; cryogenic effects in the atmosphere; physical and chemical properties of ice and snow; cryobiological issues; role of cold in the evolution of biota and humans, etc.; the cryosphere became considered as a separate Earth's sphere. Revolutionary changes in the idea of the cold world became possible due to advances in the space exploration, including observations and experiments, remote sensing, and progress in astronomy and astrophysics. The gained knowledge provides a new perspective of diverse cryogenic objects and processes in the Universe, which have no analogs on the Earth.

However, it becomes clear that the apprehension of the cold world remains limited and problematic, despite the improved instrumental facilities and the avalanche-like increase in the amount of collected data. The reason is primarily that the discovered diversity of extraterrestrial cryogenic objects, as well as the large range of scales and rates of cryogenic processes, undermines the conventional views of cold in the classical terms. The classical approach of natural sciences that study different cryogenic objects and processes separately is giving way to the apprehension of the cold world as a self-evolving complex system, with a great variability of its constituents in the scale of the Universe. This understanding of the cryosphere agrees with the principles of postnonclassical science, which aims at creating a holistic view of the world (Stepin, 2006). However, as fairly noted Oleg Bazaluk и Larysa Kharchenko, "The undervaluing of philosophy and philosophical knowledge has led to the fact that modern research in cosmology, biology and neuroscience is completely unrelated and does not enrich each other through explorations" (Bazaluk & Kharchenko, 2018: 10). This situation is typical for different fields of knowledge. Therefore, the most important methodological problem of the modern science is development of the philosophical

approaches playing a role of the integrating basis for cross-disciplinary researches (Epstein, 2016; Rovelli, 2018). In 2019 was issued the article “Why science needs philosophy” (Laplane et al., 2019). Its authors on the example of three advanced scientific research where cooperation is recognized as mutually useful, show that the contribution of philosophy can take at least four forms:

- a) Specification of scientific concepts;
- b) Critical assessment of the scientific assumptions or methods;
- c) Creating of concepts and the checked and predicted theories which help to lay new ways for empirical researches;
- d) Development of dialogue between various sciences, as well as between science and society.

The philosophical analysis allocates important semantic and conceptual problems in different fields of science. Philosophy helps to get rid of the problem or outdated assumptions, concepts, helping to stimulate scientific changes. In this respect, we discuss the methods and conceptual basis of the terrestrial and extraterrestrial cryology in terms of a new science called cryosophy (Melnikov & Gennadinik, 2011). Cryosophy studies the role of cold in the origin and evolution of life and heat-mass interactions in the world. It addresses the key features and principles of the evolution of the cryosphere and uses both classical (for simple physical and chemical systems) and synergetic (for complex and living systems) approaches, as well as information logistic methods that generate knowledge about knowledge.

Although geocryology as a particular natural science is only 100 years old, the philosophical views of cold are at least 2500 years old. To expand the perspective of the cold world, it is crucial to learn the whole history of its apprehension by the global science.

Cold: evolution of scientific views from natural philosophy to geocryology

Studies of cold date back to the ages of ancient Greek natural philosophy, which flourished between the 7th and 4th centuries BC. It was then a single science not yet divided into philosophy and natural sciences, leaving aside the more detailed later division (Rozhanskiy, 1979). Natural philosophy studied the world as a whole; the Greek thinkers tried to pick essential principles (elements) of the nature in their versatility and interactions and made their conclusions from direct observations of the natural phenomena. In that worldview system, nature was treated as *Cosmos*, an entity rather than an environment as it has been since the Modern ages. Each individual physical being in cosmos was thought to have its specific place and destination, while the cosmos as a whole was the absolute perfect (Akhutin, 1988). Correspondingly, many Greek thinkers considered cold as a universal element that controls the physical features of cosmos.

In the early history of Greek nature philosophy, cold seemed interesting as an element in the system of dichotomy. For Parmenides, warm and cold were elements like fire and earth (Aristotle, 1981). Anaximander viewed the world as a scene of interacting essential opposites extracted from the infinite (*apeiron*) which was the source of all things. The cold tends to overwhelm the warm, the dry overwhelms the wet and vice versa, while the *apeiron* maintains the overall balance and prevents the opposites from winning one over another (Kessidi, 1982). Heraclitus developed Anaximander's theory and was the first to formulate the idea of *Logos* as a universal rhythm, measure, and order. As fundamentals of dialectics, Heraclitus understood transformation as replacement of one element by another: what is cold becomes

warm and what is warm becomes cold; what is wet becomes dry and what is dry becomes wet (Kessidi, 1982). Heraclitus viewed the opposites as a consistent system making up a single whole, in which all things and phenomena could change and transform into their opposites (Kessidi, 1982: 53).

A key question at that evolution stage of science was whether cold is a physical matter or a universal property of any matter. According to Anaximenes, a Milesian philosopher, cold and warm were transient states of matter rather than specific substances. As he affirmed, anything, which undergoes contraction and condensation of matter, is cold, while anything that suffers rarefaction and distention is hot (Lebedev, 1989). Anaximenes treated air as an element of any matter, which can acquire various physical states associated with its condensation or rarefaction and thus provides the diversity of things in the surrounding world (Rozhanskiy, 1979); he imagined these changes as rhythmical respiration of Cosmos (Kessidi, 1982).

Plutarch's *On the Principles of Cold* was among earliest special treatises on the cold world. The philosopher inquires whether there exists an active principle or substance of cold (as fire is of heat) or is coldness rather a negation of warmth, as darkness is of light and rest of motion (Rozhanskiy, 1979). Plutarch insists that cold is not mere negation or privation of heat, but is rather a positive substance or force that can make change to matter like heat. Furthermore, rest in frozen things is not mere inaction but rather stability, which is due to the consolidating and compressing capacity of cold (Rozhanskiy, 1979).

The great merit of Greek philosophers was that they were the first to seek explanations for the framework role of cold in the physics of the Earth and the cosmos. Anaxagoras tried to understand how an ordered world of cosmos emerged out of the formless primordial matter; as he thought, the dense, the moist, the dark and the cold, and all the heaviest things collected in the centre and consolidated, and thus gave birth to the Earth (Rozhanskiy, 1979).

Plato and Democritus who laid the foundations of the theory of atomism tried to explain the effect of hot and cold by the action of tiny invisible particles: *atoms* (Rozhanskiy, 1979). Plato distinguished two varieties of water: "liquid" water and "fusible" water; the former refers to all fluids and the latter to solids that can melt and flow under the action of fire.

The contribution of Aristotle's physiophilosophical views into the theory of cold was the greatest. He considered cold and heat as elements producing the properties of matter by making it dense or solid (Aristotle, 1981). In his views, the opposites of cold/hot and dry/wet, combined in different ways, formed the four elements of fire, air, water, and earth (Fig. 1); cold was part of two latter elements: cold+wet=water; cold+dry=earth (Aristotle, 1981). Developing the ideas of Anaximenes and Heraclitus, Aristotle postulated the existence of a single matter common for the opposites of hot and cold (Aristotle, 1981). He was among the first thinkers to focus on the issues of cold and its role in atmospheric phenomena like hoar, dew, snow, and hail (Aristotle, 1981).

Fig. 1. Aristotle's elements and their properties

Summing up the contribution of Greek philosophers into the knowledge of cold, it is pertinent to note that the problems they formulated were actually a breakthrough for the science of that time and remain essential nowadays. The issues they covered were:

- a) cold as one of opposites in the system of natural elements (Parmenides, Heraclitus, Anaximander, Anaximenes, Aristotle, etc.);
- b) material carriers of cold (Plutarch, Empedocles, etc.);
- c) cold as a universal property of matter (Anaximenes, Aristotle, etc.);
- d) effect of cold on state change in natural objects (Aristotle, Plato, Democritus, etc.);
- e) cold as framework in the structure of the Earth (including its atmosphere) and the Cosmos (Anaxagoras, Anaximenes, Aristotle, etc.).

Of course, the ancient knowledge was insufficient to find realistic solutions and many speculative hypotheses on the nature and features of cold did not hold up. However, the very formulation of problems had a great scientific value and became precursor to the basic objectives of cryosophy thousands of years before it originated.

After the period of classical antiquity, the development of the theory of cold and its properties remained suspended for centuries, because the syncretic ancient natural philosophy dispersed into several sciences in the Hellenistic times, the natural sciences decayed in the Middle ages, etc. The interest to cold as an agent in various natural phenomena and processes rekindled during the Renaissance. The 18th century was another milestone, with Isaac Newton's law of cooling and *Scala Graduum Caloris. Calorum Descriptiones & Signa* (Scale of the Degrees of Heat. Description and Signs of Heat) that came out in 1701, where he suggested a scale of 12 degrees between the melting point of ice and body temperature. Guillaume Amontons presented his air thermometer in 1703 setting absolute zero at the point where air loses elasticity (-239.5°C). In 1750, Michael Lomonosov published his work *On the Causes of Hot and Cold* where he proved that the temperature, or the heating degree of bodies, was a measure of motion of small physical particles (Lomonosov, 1951); hence, the state when the particles stop moving corresponded to the greatest degree of cold. Johann Heinrich Lambert, a German scientist, updated the absolute zero value to -270°C in 1779. In those and other studies of that time, the apprehension of cold as affecting the structure

and properties of matter advanced actually in terms of the basic problems put forward by the Greek philosophers.

On the other hand, positivistic thinking that set in the methodology of science in the 19th century implicitly precluded turning back to ancient philosophical approaches to the nature of cold. The positivists rightfully criticized the physiophilosophical attitudes, which often imposed speculative ideas of natural objects and processes but were wrong to extrapolate that criticism onto philosophy as a whole and to negate its basic principles and ideas as off-cast “metaphysics” (Stepin, 2006). At the same time, as noted by Olga Stoliarova (Stoliarova, 2018), the principle of empiricism jointly with criticism pushed the metaphysics into the marginal background, isolated it from the empirical thinking and left in an unstable and equivocal position. That was the setting in which the observations of Haurace de Saussure, Alexander Humboldt, Alexander Middendoff, Karl Baer, Peter Kropotkin, and others created prerequisites for glaciology, a new science of ice and glaciers that appeared in the latest 18th century, as well as for geocryology, a science of permafrost that formed in the 20th century. In their early history, both glaciology and geocryology were mostly descriptive sciences based on field observations concerning the extent and physical properties of permafrost, ice, and snow.

New perspectives of the cold world in postnonclassical science

The scope of objects and lines of research about the cold world has extended markedly at the turn of the 21st century. Many studies of cryogenic effects have been closely related to the classical subjects of geology and geography, as well as to various problems of physics, chemistry, cosmology, climatology, ecology, pedology, biology, medical sciences, etc., which led to changes in the axiological comprehension of cold. Now it became clear that cold is a yet underestimated resource rather than something hostile (Melnikov & Fedorov, 2018; Fedorov, 2019). A few years ago, the term *cryodiversity* (Melnikov & Gennadinik 2018) was coined to help understanding the diversity of objects and phenomena associated with cold and phase change of H₂O, as well as forms and properties of ice as a focus of theoretical research. The properties of ice can be summarized in a model of a multi-function system (Fig. 2) with six main components plotted in the scales of space (ice as a physical system and a natural material), energy (ice as a physicochemical system and a phase state), and time (ice as a system of information and control) (Melnikov & Gennadinik, 2011).

The concept of cryodiversity covers multiple biotic and abiotic complex systems, such as cryophilic bacteria that live in permafrost, atmospheric precipitation, gas hydrates, etc.

Cryodiversity also refers to cryogenic effects in the extraterrestrial space, which have been increasingly more widely investigated since the middle of 20 century. The evolution and properties of the cryosphere in different planets or other celestial bodies make part of the basic knowledge indispensable for the future exploration of the Universe. In this respect, the concept of *cryogenic type planets* has been used in rapidly progressing planetary cryology, a recent natural science that deals with the principles of existence, formation, space-time evolution, structure, and properties of both terrestrial and extraterrestrial frozen rocks containing H₂O, CO₂, CH₄, and some other substances in liquid, solid, and gaseous states, as well as cryogenic phenomena and processes.

Frozen rocks (permafrost) belong to the cryosphere which makes up a sphere of some planets in the Solar System and their satellites, comets, and asteroids, where water, methane, ammonia, and carbon dioxide in different phase states can coexist. Planetary cryology

studies frozen rocks, including accumulations of snow and ice consisting of H_2O (various modifications), CO_2 , CH_4 , etc., above and below the ground surface (Komarov & Isaev, 2010). Cryogenic phenomena and processes on different planets are extremely diverse depending on their physicochemical features, core state, orbits, gravitation, density of atmosphere, etc.

Fig. 2. Ice as a multifunction system (author of the scheme — Victor Gennadinik).

Many such effects would be hard to imagine from the viewpoint of the terrestrial conditions. According to one of versions of the researchers, water on the surface of Gliese 436b (Fig. 3), an extrasolar planet discovered in 2004 in the constellation of Leo, can remain solid at a temperature of $\sim 300^{\circ}\text{C}$. The reason is that water converts to ice under extremely high pressure produced by gravity. That is why it was called the *planet of burning ice* (Shiga, 2007; The Planet of Burning Ice). On the other hand, interstellar ice composed of water, methanol, and ammonia at temperatures between -120°C and -210°C can exist in a honey-like viscous state under UV irradiation (Tachibana et al., 2017).

Fig. 3. Internal structure of Gliese 436b. Borrowed from <https://astronaut.com>

Prior to these discoveries, H_2O ice in space bodies was found out to exist in various crystalline modifications, which differ markedly in their thermodynamics: ice I is common to Earth and Mars while ice varieties II to VIII exist at high pressures above 10^2 MPa (Komarov & Isaev, 2010). The domains of ice varieties III, V, VI, and VII border that of liquid whereas the domains of II and III border the solid state region of other varieties.

H_2O ice is common to the Earth as well as to Mars and icy moons of Jupiter (Europe, Ganymede and Callisto) and Saturn (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Iapetus). The H_2O ice may coexist with other ice types: CO_2 ice on the polar caps of Mars; NH_3 ice on some moons of Saturn (Titan and Enceladus) and Neptune (Triton), and CH_4 ice also on Neptune and Triton (Komarov & Isaev, 2010).

In some cases, climate change on the Earth can produce cryogenic effects which were previously thought to be possible on other planets only. This is, for instance, formation of gas explosion craters in the Yamal Peninsula, a phenomenon similar to cryovolcanism reported from some celestial bodies (Kizyakov et al., 2017, 2018).

As shown by studies of extraterrestrial cryodiversity, the concept of *cold* is actually relative when applied to physical processes on the scale of the Universe (e.g., the ice varieties that form at $>0^{\circ}\text{C}$). This concept is also used metaphorically to describe some types of matter in the space, which may have positive temperatures, such as *cold dark matter* or *CMB cold*

spot. It is also used in this sense in the cosmogonic theory of Otto Schmidt (Schmidt, 1962) claiming that the Earth and other planets of the Solar System formed out of cold solid bodies of the gas-dust cloud around the Sun.

Fig. 4. Ice and microorganisms in frozen ground: (a) layers of segregated ice in clay silt; (b, c) cells of different shapes in ice layers; (d) mineral coat over a microbial cell; (e) cells of *Bacillus cereus* in an ice layer in kaolin (inset at magn $\times 30$); (f) cells of *Bacillus* sp. in an ice lens.

Cryodiversity shows up also in a large range of rates of cryogenic processes: a snowflake can form in the troposphere for fractions of a second; it falls on the ground from the height of 3000 m in 30 minutes; if it falls on the Antarctic ice sheet, it will reach its base in 500,000 years. People commonly can perceive the relatively short processes commensurate with a human lifespan and rarely think about geological-scale changes. Meanwhile, cold can maintain very long life in organisms unusual for our perception of biological time. For instance, biological processes are very slow in paleobacteria that remain viable in permafrost for many thousands

of years (Fig. 4) (Brouchkov et al 2016, 2017; Margesin et al 2016). Ice can slow down biotic processes due to its properties: low dielectric permittivity and magnetic susceptibility which reduce electromagnetic fields; high stiffness which resists mechanic impacts; low permeability which decelerates mass transport; high heat capacity and anomalous specific heat of melting which damp temperature variations. Thereby, the interaction between an object and its environment in the cryosphere is basically restricted to weak gravity effects and very slow diffusion. For this reason, the cryosphere of other bodies in the Universe may be a candidate for a medium favorable for the dawn of extraterrestrial life.

When studying cryodiversity in terms of cryosophy, it is important to take into account all elements in the system of cold; otherwise, missing even a single element will lead to misinterpretation of the system's state. The Earth's cryosphere is a second-order system in the supersystem of the Universe-scale cryosphere; in its turn, it has its subsystems, such as different $<0\text{ }^{\circ}\text{C}$ atmospheric layers with their specific features, cryogenic components on the ground surface, permafrost, and gas hydrates. Thus, cryosophy is a methodological paradigm creating a holistic perspective of the cryosphere in the context of interdisciplinary postnonclassical science. This is a trend toward a general scientific world view based on the principles of universal evolutionism which brings together the ideas of systemic and evolutionary approaches to the study of complex self-evolving systems (Stepin 2006: 331; Bazaluk, 2015; Ursul & Ursul 2017).

According to the views of Vyacheslav Stepin (Stepin, 2006), complex self-evolving systems are arranged hierarchically and can generate new hierarchic levels. Note that the philosophical system of Aristotle likewise presents the world as a hierarchic system with dynamically interacting elements of different levels. In this respect, there is overlap between the objectives of Greek natural philosophy and the modern postnonclassical science. The ancient thinkers had a syncretic view of the world and put forward basic problems of scientific knowledge, but they could not find the solutions with the limited methodological and instrumental facilities of that time. Meanwhile, the science at the postnonclassical stage has acquired new features as prerequisite for the creation of an advanced worldview. The idea of such holistic approach remained for a long time a remote ideal until real opportunities appeared in the 1970s to bring together the views of the living and nonliving nature and the society based on general scientific principles. These principles take into account the specificity of each field of science and, at the same time; act as invariants in the diversity of various ontologies (Stepin, 2006). In this context, cryosophy is an attempt of joining the three existential complexity levels, with a focus on cryogenic phenomena.

Conclusions

Philosophical apprehension of cold dates back to the ages of Ancient Greece. Aristotle, Plutarch, Heraclitus, Plato, Democritus, Anaximenes, Anaxagorus, and Anaximander were the first to formulate the basic problems concerning the cold matter, its properties and role in the world. It was yet impossible to find the solutions in terms of the metaphysical worldview of that time. Paradoxically, it took more than two thousand years to approach the understanding of the problems put forward by the natural philosophy of the classical antiquity. It became feasible due to new facilities for space-borne studies of cryodiversity; a new axiological paradigm of cold with its environment-forming and resource values; interdisciplinary integration of natural, humanitarian, mathematical, and engineering sciences that study various objects and processes associated with cold; viewing the cryosphere as a complex system.

The scientific problems formulated by Greek thinkers are developed in cryosophy. The role of cold in the system of opposites is often considered in the modern science in terms of dialectics. For instance, the phase transition of ice from solid to liquid and back illustrates the principle of transition from quantity into quality. Aristotle, Plutarch and other philosophers tried to understand the role of cold in the formation of the elements at the base of natural objects, while cryosophy studies transformations and interactions of hydrogen and oxygen, which are primary and secondary elements, with their hydrogen bonds being the base of both inorganic and organic matter. The very evolution of the Universe, since the matter emerged from the elementary particles of protons, neutrons, and electrons at the big bang, has been associated with hydrogen that formed first (together with helium) upon cooling (Melnikov & Gennadinik, 2012). The systemic value of cold in the physical structure of the Earth and the extraterrestrial space, which interested Anaxagoras and other thinkers of Ancient Greece, is the principal subject of cryosophical research on cryogenic systems in the terrestrial and extraterrestrial evolution. The investigation into the effect of cold on the structure and state of natural objects initiated by Aristotle, Plato, and Democritus still brings about new discoveries.

However, unlike Greek natural philosophy, which pretended to be a universal syncretic science, cryosophy is a kind of integrator, which attracts different fields of knowledge related to the cold world and builds a framework for its ontology. The integrating and framework role of cryosophy is consistent with the global trends in philosophy of science evolving from a “real science” to its epistemological comprehension through generalizing models and evolution principles (Lebedev & Kos'kov, 2014). This self-comprehension of the science began at its nonclassical stage and has been progressively more important in the postnonclassical history of its epistemology and philosophy. In the case of cryosophy, it has been the first attempt to formulate a system of cognitive views of terrestrial and extraterrestrial cryogenic objects, phenomena, and processes integrated into the emerging holistic scientific worldview.

References

- Akhutin, Anatoly. (1988) *Concept “Nature” in Antiquity and Modern times*. Moscow: Nauka. (In Russian)
- Aristotle. (1981) *Works. Book 3*. Moscow: Mysl'. (In Russian)
- Bazaluk, Oleg. (2015) The Basic Postulates of the Universal Evolution Model “Evolving Matter”. *Philosophy and Cosmology* 2015 (Vol. 14): 11-20.
- Bazaluk, Oleg, and Larysa Kharchenko. (2018) The Philosophy of the Cosmos as the New Universal Philosophical Teaching about Being. *Philosophy and Cosmology*, Vol. 21, 6–13. <https://doi.org/10.29202/phil-cosm/21/1>
- Brouchkov, Anatoly et al. (2016) Is the ancient permafrost bacteria able to keep DNA stable? *Journal of Genetics*, Vol. 95, Issue. 4, 1003–1007. <https://doi.org/10.1007/s12041-016-0708-0>
- Brouchkov, Anatoly et al. (2017) Permafrost bacteria in biotechnology: biomedical applications. *Psychrophiles: From Biodiversity to Biotechnology*, Springer, 541–554. https://doi.org/10.1007/978-3-319-57057-0_23
- Epstein, Mikhail. (2016) *From Knowledge to Creativity: How the Humanities Can Change the World*. Moscow: Tsentr gumanitarnykh initsiativ. (In Russian)
- Fedorov, Roman. (2019) Cryogenic Recourses: ice, snow, and permafrost in traditional subsistence systems in Russia. *Resources*. Vol. 8, Issue 1, 17. <https://doi.org/10.3390/resources8010017>

- Fragments of early Greek philosophers. Part 1. From epic theocosmogony before emergence of atomistics.* (1989). Moscow: Nauka (In Russian)
- Kessidi, Feoharij. (1982) *Heraclitus*. Moscow: Mysl'. (In Russian)
- Kizyakov, Alexander et al. (2017) Comparison of Gas Emission Crater Geomorphodynamics on Yamal and Gydan Peninsulas (Russia), Based on Repeat Very-High-Resolution Stereopairs. *Remote Sensing*, Vol. 9 (10), 10-23. <https://doi.org/10.3390/rs9101023>
- Kizyakov, Alexander et al. (2018) Microrelief associated with gas emission craters: remote sensing and field-based study. *Remote Sensing*. Vol. 10, Issue 5, 677. <https://doi.org/10.3390/rs10050677>
- Komarov, Ilya, and Vladislav Isaev. (2010) *Cryology of Mars and other Solar System Planets*. Moscow: Nauchnyi Mir. (in Russian)
- Laplane, Lucie et al. (2019) Why science needs philosophy. *PNAS*, Vol. 116, Issue. 10, 3948–3952. <https://doi.org/10.1073/pnas.1900357116>
- Lebedev, Sergej, and Sergej Kos'kov. (2014) *Epistemology and philosophy of science*. Moscow: Akademicheskij proekt. (In Russian)
- Lomonosov, Mihail. About the reason of warmth and an icy cold. Complete works. (1951) *Book 2: Works on physics and chemistry*. Moscow–Leningrad: AN SSSR, 57–61. (In Russian)
- Margesin, Rosa et al. (2016) *Glaciimonas frigoris* sp. nov., a psychrophilic bacterium isolated from ancient Siberian permafrost sediment, and emended description of the genus *Glaciimonas*. *International Journal of Systematic and Evolutionary Microbiology*, Vol. 66, Issue 2, 744–748. <https://doi.org/10.1099/ijsem.0.000783>
- Melnikov, Vladimir, and Victor Gennadinik. (2011) Criosophy — a system of ideas of the cold world. *Earth's Criosphere (Kriosfera Zemli)*, Vol. 15, Issue 4, 3–8. (In Russian)
- Melnikov, Vladimir, and Victor Gennadinik. (2018) Cryodiversity: the World of Cold on the Earth and in the Solar System. *Philosophy and Cosmology*, Vol. 20, 43–54. <https://doi.org/10.29202/phil-cosm/20/4>
- Melnikov, Vladimir, and Roman Fedorov. (2018) The role of natural cryogenic resources in traditional subsistence systems of the peoples of Siberia and the Far East. *Tomsk State University Journal (Vestnik Tomskogo gosudarstvennogo universiteta)*, Vol. 426, 133–141. (In Russian)
- Rovelli, Carlo. (2018) Physics needs philosophy. Philosophy needs physics. *Foundations of Physics*, Vol. 48, 481. <https://doi.org/10.1007/s10701-018-0167-y>
- Rozhanskij, Ivan. (2000) Physical views of Plutarch. *Nature philosophy in antiquity and in the Middle Ages*. Moscow: Progress-Tradiciya, 2000: 91–102. (In Russian)
- Rozhanskij, Ivan. (1979) *Development of natural sciences during antiquity era. Early Greek science about the nature*. Moscow: Nauka. (In Russian)
- Shiga, David. (2007) Strange alien world made of “hot ice”. *New Scientist*. 16 May 2007. URL: <https://www.newscientist.com/article/dn11864-strange-alien-world-made-of-hot-ice/>
- Shmidt, Otto. (1962) *Origin of the Earth and Planets*. Moscow: Nauka. (In Russian)
- Stepin, Vyacheslav. (2006) *Philosophy of science. Common problems*. Moscow: Gardariki. (In Russian)
- Stoliarova, Olga. Whether the empirical science can serve as justification of metaphysics? (2018) *Tomsk State University Journal. Philosophy, Sociology, Politology (Vestnik Tomskogo gosudarstvennogo universiteta. Filosofiya. Sociologiya. Politologiya)*. Vol. 43, 5–18. <https://doi.org/10.17223/1998863X/43/1> (In Russian)

-
-
- Tachibana, Shogo et al. (2017) Liquid-like behavior of UV-irradiated interstellar ice analog at low temperatures. *Science Advances*, Vol. 3, Issue 9, eaao2538. <https://doi.org/10.1126/sciadv.aao2538>
- The Planet of Burning Ice. *Astronaut*. URL: <https://astronaut.com/the-planet-of-burning-ice/>
- Ursul, Arkady, and Tatiana Ursul. (2017) Education and Globalistics. *Future Human Image*. 7, 136–153.