THE BIOSPHERE

VLADIMIR I. VERNADSKY

Foreword by
Lynn Margulis
Mauro Ceruti
Stjepko Golubic
Ricardo Guerrero
Nubuo Ikeda
Natsuki Ikezawa
Wolfgang E. Krumbein
Andrei Lapo
Antonio Lazcano
David Suzuki
Crispin Tickell
Malcolm Walter
Peter Westbroek

Introduction by
Jacques Grinevald

Translated by
David B. Langmuir

Revised and Annotated by
Mark A. S. McMenamin

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The Biosphere in the Cosmic Medium

1 The face of the Earth[7] viewed from celestial space presents a unique appearance, different from all other heavenly bodies. The surface that separates the planet from the cosmic medium is the *biosphere*, visible principally because of light from the sun, although it also receives an infinite number of other radiations from space, of which only a small fraction are visible to us. We hardly realize the variety and importance of these rays, which cover a huge range of wavelengths.

Our understanding is full of gaps, but improved detectors are rapidly expanding our knowledge of their existence and variety. Certainly they make the empty cosmic regions different from the ideal space of geometry![8]

Radiations reveal material bodies and changes in the cosmic medium. One portion appears as energy through transitions of states, and signals the movements of aggregates of quanta, electrons and charges. The aggregates, which as a whole may remain motionless, control the movements of their separate elements.

There are also rays of particles (the most-studied are electrons) which often travel at nearly the same speed as waves, and result from transitions in separate elements of the aggregates. Both kinds of rays are powerful forms of energy, and cause observable changes when they pass through material bodies.

2 For the moment, we can neglect the influence of particle radiation on geochemical phenomena in the biosphere, but we must always consider the radiations from transitions of energy states. These will appear as light, heat, or electricity according to their type and wavelength, and produce transformations in our planet.

These rays cover a known range of forty octaves in wavelength (10^{-8} cm to kilometers), of which the visible spectrum is one octave.[9] This immense range is constantly being extended by scientific discovery, but only a few of the forty octaves have thus far affected our view of the cosmos.

The radiations that reach our planet from the cosmos amount to only four and one-half octaves. We explain the absence of the other octaves on the Earth's surface by absorption in the upper atmosphere.

The best-known radiations come from the sun — one octave of light rays, three of infrared radiation, and a half-octave of ultraviolet; the last half-octave being, doubtless, only a small fraction of the total ultraviolet from the sun, most of which is retained by the stratosphere. (§115)

6 "Biospherology" is the term now used by some for study of the biosphere (see Guegamian, 1980). Others, such as NASA, use the term "biospherics."

7 In this first phrase Vernadsky echoes the title and opening sentence of Eduard Suess's influential geological compendium, *Die Antlitz der Erde* [*The Face of the Earth*] (Suess, 1883-1909, p. 1). Suess wrote:

"If we imagine an observer to approach our planet from outer space, and, pushing aside the belts of red-brown clouds which obscure our atmosphere, to gaze for a whole day on the surface of the earth as it rotates beneath him, the feature beyond all others most likely to arrest his attention would be the wedge-like outline of the continents as they narrow away to the South."

For more information on Suess's influence, see Greene (1982). Vernadsky admired the inductive approach utilized by Suess in this book.

8 Vernadsky reached the conclusion early on that radiation from the cosmos played a large role in the development of life.

9 "Octave" is a term used in both music and physical science. It means the same thing in both: a span over which a wavelength is halved or doubled.

3 A new character is imparted to the planet by this powerful cosmic force. The radiations that pour upon the Earth cause the biosphere to take on properties unknown to lifeless planetary surfaces, and thus transform the face of the Earth. Activated by radiation, the matter of the biosphere collects and redistributes solar energy, and converts it ultimately into free energy capable of doing work on Earth.

The outer layer of the Earth must, therefore, not be considered as a region of matter alone, but also as a region of energy and a source of transformation of the planet. To a great extent, exogenous cosmic forces shape the face of the Earth, and as a result, the biosphere differs historically from other parts of the planet. This biosphere plays an extraordinary planetary role.

The biosphere is at least as much a *creation of the sun* as a result of terrestrial processes. Ancient religious intuitions that considered terrestrial creatures, especially man, to be *children of the sun* were far nearer the truth than is thought by those who see earthly beings simply as ephemeral creations arising from blind and accidental interplay of matter and forces. Creatures on Earth are the fruit of extended, complex processes, and are an essential part of a harmonious[10] cosmic mechanism, in which it is known that fixed laws apply and chance does not exist.[11]

4 We arrive at this conclusion via our understanding of the matter of the biosphere — an understanding that had been profoundly modified by contemporary evidence that this matter is the direct manifestation of cosmic forces acting upon the Earth.

This is not a consequence of the extraterrestrial origin of matter in the biosphere, perhaps the majority of which has fallen from space as cosmic dust and meteorites. This foreign matter cannot be distinguished in atomic structure from ordinary terrestrial matter.

We must pause before entering the domain of terrestrial phenomena, because our ideas about the unforeseen character of matter on this planet are going through great transformations, upsetting our understanding of geology.

The identity of structure[12] between earthly matter and exogenic cosmic matter is not limited to the biosphere, but extends through the whole terrestrial crust; i.e., through the lithosphere, which extends to a depth of 60-100 kilometers, and interfaces with the biosphere at its outermost part. (§89)

Matter in the deeper parts of the planet shows the same identity, although it may have a different chemical composition.

10 Cf. the Tyutchev epigraph above.

11 Vernadsky is quite explicit here in his challenge to the "randomness" component of materialistic darwinism. This component has been expressed, complete with reference to the biosphere, by J. Monod (1971, p. 98):

"Randomness caught on the wing, preserved, reproduced by the machinery of invariance and thus converted into order, rule, necessity. A *totally* blind process can by definition lead to anything; it can even lead to vision itself. In the ontogenesis of a functional protein are reflected the origin and descent of the whole biosphere."

12 Presumably Vernadsky here means identity of atomic structure.

Matter from these regions seems, however, not to penetrate to the Earth's crust even in small amounts, and can therefore be ignored in studies of the biosphere.[13]

5 The chemical composition of the crust has long been regarded as the result of purely geological causes. Explanations of it have been sought by invoking the action of waters (chemical and solvent), of the atmosphere, of organisms, of volcanic eruptions, and so on, assuming that geological processes and the properties of chemical elements have remained unchanged.[14]

Such explanations presented difficulties, as did other and more complicated ideas that had been proposed. The composition was considered to be the remains of ancient periods when the Earth differed greatly from its present state. The crust was regarded as a scoria formed on the terrestrial surface from the once-molten mass of the planet, in accordance with the chemical laws that apply when molten masses cool and solidify.[15] To explain the predominance of lighter elements, reference was made to cosmic periods before the formation of the crust. It was thought that heavier elements were collected near the center of the Earth, during its formation as a molten mass thrown off from a nebula.

In all these theories, the composition of the crust was seen as a result of strictly geological phenomena. Chemical changes in composition of the crust were attributed to geological processes acting at lower temperatures, whereas isotopic changes in crustal composition were attributed to processes acting at higher temperatures.

6 These explanations are decisively contradicted by newly established laws which are in accord with recent results indicating that the chemical composition of stars is marked by previously unsuspected complexity, diversity, and regularity.[16]

The composition of the Earth, and particularly its crust, has implications that transcend purely geological phenomena. To understand them, we must direct our attention to the composition of all cosmic matter and to modifications of atoms in cosmic processes. New concepts are accumulating rapidly in this speculative field. Comparatively little theoretical analysis has been done, however, and deductions that might be justifiable have seldom been made explicit. The immense importance and unexpected consequences of these phenomena cannot, however, be disregarded. Three aspects of these phenomena can be

13 Study of deep seated kimberlite pipe eruptions (mantle rocks that somehow penetrated to Earth's surface) demonstrate that this can no longer be strictly the case; see Nixon, 1973; and Cox, 1978.

14 These are the fundamental assumptions of geological actualism.

15 Such an assumption led Lord Kelvin (see Hallam, 1992, p. 124; and Kelvin, 1894) to an erroneous calculation of the age of Earth.

16 Here Vernadsky is without doubt referring to the work of Einar Hertzsprung and Henry Norris Russell. Hertzsprung's pioneering research advanced the knowledge concerning the color of stars. Star color can be used as an index to star temperature. Russell's work greatly extended the list of stars with known luminosities (as calculated by parallax measurements). Plots of stellar luminosity to surface temperature, published by Russell beginning around 1915, established the "main sequence" of stars in the universe. Using the theoretical Hertzsprung-Russell diagram, one may plot lines of constant stellar radius against an ordinate axis of luminosity and an abcissa axis of effective temperature. Thus if one knows the luminosity and effective temperature of a star, it is possible to calculate its radius.

It became possible to remotely analyse the composition of stars when the lines in the solar spectrum (named Fraunhofer lines after the glass maker and optician Joseph Fraunhofer) were explained by photographer W. H. Fox Talbot (1800-1877) and Gustav Kirchoff as absorption lines characteristic (with absorption occuring as sunlight passes through the cooler, outer gaseous layers of the Sun) for specific excitation states of particular elements.

given preliminary discussion, namely: 1. the peculiar positions of the elements of the crust in Mendeleev's periodic system;[17] 2. their complexity; 3. the non-uniformity of their distribution.

Elements with even atomic number clearly predominate in the Earth's crust.[18] We cannot explain this by known geological causes. Moreover, the same phenomenon is more marked in meteorites, the only bodies foreign to the Earth that are immediately accessible for study.[19]

The two other aspects seem even more obscure. The attempts to explain them by geological laws or causes apparently contradict well-known facts. We cannot understand the hard facts of the complexity of terrestrial elements; and still less, their fixed isotopic compositions. Isotopic ratios in various meteorites have been shown to be the same,[20] in spite of great differences in the history and provenance of these meteorites.

Contrary to previous beliefs, it is becoming impossible to perceive the laws that govern the Earth's composition in terms of purely geological phenomena, or merely in terms of "stages" in the Earth's history. The latter explanation fails on account of the fact that there is neither a similarity of the deeper portions of our planet with the composition of meteorites, nor, as in meteorites,[21] an even mix of both lighter chemical elements and of denser iron in rocks of either Earth's crust or rocks from depth. The hypothesis that elements will be distributed according to weight, with the heaviest accumulating near the center, during the formation of the Earth from a nebula, does not agree with the facts. The explanation can be found neither in geological and chemical phenomena alone, nor in the history of the Earth considered in isolation. The roots lie deeper, and must be sought in the history of the cosmos, and perhaps in the structure of chemical elements.[22]

This view of the problem has recently been confirmed, in a new and unexpected way, by the similarity in composition between the Earth's crust and the sun and stars. The likeness in composition of the crust and the outer portions of the sun was noted by Russell as early as 1914, and the resemblances have become more marked in the latest work on stellar spectra.[23] Cecilia H. Payne[24] lists heavier stellar elements in descending order of abundance as follows: silicon, sodium, magnesium, aluminum, carbon, calcium, iron (more than one percent); zinc, titanium, manganese, chromium, potassium (more than one per mil).

This pattern clearly resembles the order of abundance in the

17 See Mendeleev, 1897.

18 See Oddo, 1914.

19 See Harkins, 1917.

20 This observation was later used to date all of the meteorites (and Earth itself) to at age of approximately 4.6 billion years based on abundances of Strontium-87 and Rubidium-87 (Reynolds, 1960).

21 See Farrington, 1901.

22 Vernadsky was overinterpreting his data here. Iron and nickel went to Earth's core at a time when the planet was completely or partially melted, early in its history. The flow of dense liquid toward the core released additional heat (as thermal [kinetic] energy converted from potential energy) and caused additional melting of rock.

23 See Norris, 1919.

24 See Payne, 1925.

Earth's crust: oxygen, silicon, aluminum, iron, calcium, sodium, potassium, magnesium.

These results, from a new field of study, show striking similarities between the chemical compositions of profoundly different celestial bodies. This might be explained by a material exchange taking place between the outer parts of the Earth, sun, and stars. The deeper portions present another picture, since the composition of meteorites and of the Earth's interior is clearly different from that of the outer terrestrial envelope.

7 We thus see great changes occurring in our understanding of the composition of the Earth, and particularly of the biosphere. We perceive not simply a planetary or terrestrial phenomenon, but a manifestation of the structure, distribution, and evolution of atoms throughout cosmic history.

We cannot explain these phenomena, but at least we have found that the way to proceed is through a new domain of phenomena, different from that to which terrestrial chemistry has so long been limited. Viewing the observed facts differently, we know *where* we must seek the solution of the problem, and where the search will be useless. The structure of the cosmos manifests itself in the outer skin or upper structure of our planet. We can gain insight into the biosphere only by considering the obvious bond that unites it to the entire cosmic mechanism.[25]

We find evidence of this bond in numerous facts of history.

The Biosphere as a Region of Transformation of Cosmic Energy

8 The biosphere may be regarded as a region of transformers that convert cosmic radiations into active energy in electrical, chemical, mechanical, thermal, and other forms. Radiations from all stars enter the biosphere, but we catch and perceive only an insignificant part of the total; this comes almost exclusively from the sun.[26] The existence of radiation originating in the most distant regions of the cosmos cannot be doubted. Stars and nebulae are constantly emitting specific radiations, and everything suggests that the penetrating radiation discovered in the upper regions of the atmosphere by Hess[27] originates beyond the limits of the solar system, perhaps in the Milky Way, in nebulae, or in stars of the Mira Ceti type.[28] The importance of this will not be clear for some time,[29] but this penetrating cosmic radiation determines the character and mechanism of the biosphere.

25 This view is also developed in the works of Alexandr E. Fersman (1933, 1934, 1937 and 1939). Fersman, Vernadsky's most influential student (Vernadsky, 1985; and Fersman, 1945), outlived his mentor by only a few months (Backlund, 1945). Fersman's work is not surprisingly an extension of the Vernadskian research program (Saukov, 1950).

26 And of that we receive only one half billionth of the total solar output (Lovins, Lovins, Krause, and Bach, 1981).

27 See Hess, 1928.

28 Mira Ceti is a long period variable star. Variable stars show periodic variations in brightness and surface temperature. Mira Ceti has an average period of 331 days.

29 Here Vernadsky anticipates the discovery of cosmic background radiation (Weinberg, 1988).

The action of solar radiation on earth-processes provides a precise basis for viewing the biosphere as both a terrestrial and a cosmic mechanism. The sun has completely transformed the face of the Earth by penetrating the biosphere, which has changed the history and destiny of our planet by converting rays from the sun into new and varied forms of energy. At the same time, the biosphere is largely the product of this radiation.

The important roles played by ultraviolet, infrared, and visible wavelengths are now well-recognized. We can also identify the parts of the biosphere that transform these three systems of solar vibration, but the mechanism of this transformation presents a challenge which our minds have only begun to comprehend. The mechanism is disguised in an infinite variety of natural colors, forms and movements, of which we, ourselves, form an integral part. It has taken thousands of centuries for human thought to discern the outlines of a single and complete mechanism in the apparently chaotic appearance of nature.

9 In some parts of the biosphere, all three systems of solar radiation are transformed simultaneously; in other parts, the process may lie predominantly in a single spectral region. The transforming apparatuses, which are always natural bodies, are absolutely different in the cases of ultraviolet, visible and thermal rays.

Some of the ultraviolet solar radiation is entirely absorbed,[30] and some partly absorbed, in the rarefied upper regions of the atmosphere; i.e., in the stratosphere, and perhaps in the "free atmosphere", which is still higher and poorer in atoms. The stoppage or "absorption" of short waves by the atmosphere is related to the transformation of their energy. Ultraviolet radiation in these regions causes changes in electromagnetic fields, the decomposition of molecules, various ionization phenomena, and the creation of new molecules and compounds. Radiant energy is transformed, on the one hand, into various magnetic and electrical effects; and on the other, into remarkable chemical, molecular, and atomic processes. We observe these in the form of the aurora borealis, lightning, zodiacal light, the luminosity that provides the principal illumination of the sky on dark nights, luminous clouds, and other upper-atmospheric phenomena. This mysterious world of radioactive, electric, magnetic, chemical, and spectroscopic phenomena is constantly moving and is unimaginably diverse.

These phenomena are not the result of solar ultraviolet radia-

30 By ozone.

tion alone. More complicated processes are also involved. All forms of radiant solar energy outside of the four and one-half octaves that penetrate the biosphere (§2) are "retained"; i.e., transformed into new terrestrial phenomena. In all probability this is also true of new sources of energy, such as the powerful torrents of particles (including electrons) emitted by the sun, and of the material particles, cosmic dust, and gaseous bodies attracted to the Earth by gravity.[31] The role of these phenomena in the Earth's history is beginning to be recognized.

They are also important for another form of energy transformation — living matter. Wavelengths of 180-200 nanometers are fatal[32] to all forms of life, destroying every organism, though shorter or longer waves do no damage. The stratosphere retains all of these destructive waves, and in so doing protects the lower layers of the Earth's surface, the region of life.

The characteristic absorption of this radiation is related to the presence of ozone (the ozone screen (§115), formed from free oxygen — itself a product of life).

10 While recognition of the importance of ultraviolet radiation is just beginning, the role of radiant solar heat or infrared radiation has long been known, and calls for special attention in studies of the influence of the sun on geologic and geochemical processes. The importance of radiant solar heat for the existence of life is incontestable; so, too, is the transformation of the sun's thermal radiation into mechanical, molecular (evaporation, plant transpiration, etc.), and chemical energy. The effects are apparent everywhere — in the life of organisms, the movement and activity of winds and ocean currents, the waves and surf of the sea, the destruction of rock and the action of glaciers, the formation and movements of rivers, and the colossal work of snow and rainfall.

Less fully appreciated is the role that the liquid and gaseous portions of the biosphere play as accumulators and distributors of heat. The atmosphere, the sea, lakes, rivers, rain, and snow actively participate in these processes. The world's ocean acts as a heat regulator,[33] making itself felt in the ceaseless change of climate and seasons, living processes, and countless surface phenomena. The special thermal properties of water,[34] as determined by its molecular character, enable the ocean to play such an important role in the heat budget of the planet.

The ocean takes up warmth quickly because of its great specific heat, but gives up its accumulated heat slowly because of

31 Earth's magnetic field actually plays a more important role in these phenomena, as demonstrated by the Van Allen Radiation Belts (see Manahan, 1994, p. 287, fig. 9.9).

32 Certain bacteria can survive such irradiation.

33 In other words, a maritime influence greatly moderates climate on land.

34 Particularly its high heat capacity.

feeble thermal conductivity.[35] It transforms the heat absorbed from radiation into molecular energy by evaporation, into chemical energy through the living matter which permeates it, and into mechanical energy by waves and ocean currents. The heating and cooling of rivers, air masses, and other meteorological phenomena are of analogous force and scale.

11 The biosphere's essential sources of energy do not lie in the ultraviolet and infrared spectral regions, which have only an indirect action on its chemical processes. It is *living matter* — the Earth's sum total of living organisms — that transforms the radiant energy of the sun into the active chemical energy of the biosphere.

Living matter creates innumerable new chemical compounds by photosynthesis, and extends the biosphere at incredible speed as a thick layer of new molecular systems. These compounds are rich in free energy in the thermodynamic field of the biosphere. Many of the compounds, however, are unstable, and are continuously converted to more stable forms.

These kinds of transformers contrast sharply with terrestrial matter, which is within the field of transformation of short and long solar rays through a fundamentally different mechanism. The transformation of ultraviolet *and infrared* radiation takes place by action on atomic and molecular substances that were created entirely independently of the radiation itself. Photosynthesis, on the other hand, proceeds by means of complicated, specific mechanisms *created by photosynthesis itself.* Note, however, that photosynthesis can proceed only if ultraviolet[36] and infrared[37] processes are occurring simultaneously, transforming the energy in these wavelengths into active terrestrial energy.

Living organisms are distinct from all other atomic, ionic, or molecular systems in the Earth's crust, both within and outside the biosphere. The structures of living organisms are analogous to those of inert matter, only more complex. Due to the changes that living organisms effect on the chemical processes of the biosphere, however, living structures must not be considered simply as agglomerations of inert stuff. Their energetic character, as manifested in multiplication, cannot be compared geochemically with the static chemistry of the molecular structures of which inert (and *once*-living) matter are composed.

While the chemical mechanisms of living matter are still unknown, it is now clear that photosynthesis, regarded as an energetic phenomenon in living matter, takes place in a particular chemical environment, and also within a thermodynamic field that differs from that of the biosphere's. Compounds that are stable within the thermodynamic field of living matter become unstable when, following death of the organism, they enter the thermodynamic field of the biosphere[38] and become a source of free energy.*

The Empirical Generalization and the Hypothesis

12 An understanding of the energetic phenomena of life, as observed in a geochemical context, provides proper explanation for the observed facts, as outlined above. But considerable uncertainties exist, on account of the state of our biological knowledge relative to our knowledge of *inert matter*. In the physical sciences, we have been forced to abandon ideas, long thought to be correct, concerning the biosphere and the composition of the crust. We have also had to reject long established, but purely geologic explanations (§6). Concepts that appeared to be logically and scientifically necessary have proved to be illusory. Correcting these misconceptions has had entirely unexpected effects upon our understanding of the phenomena in question.

The study of life faces even greater difficulties, because, more than in any other branch of the sciences, the fundamental principles have been permeated with philosophical and religious concepts alien to science.[39] The queries and conclusions of philosophy and religion are constantly encountered in ideas about the living organism. Conclusions of the most careful naturalists in this area have been influenced, for centuries, by the inclusion of cosmological concepts that, by their very nature, are foreign to science. (It should be added that this in no way makes these cosmological concepts less valuable or less profound.) As a consequence, it has become extremely difficult to study the big questions of biology and, at the same time, to hold to scientific methods of investigation practiced in other fields.

13 The vitalistic and mechanistic representations of life are two reflections of related philosophical and religious ideas that are not deductions based upon scientific facts.[40] These representations hinder the study of vital phenomena, and upset empirical generalizations.

Vitalistic representations give explanations of living phenomena that are foreign to the world of models — scientific general-

35 Vernadsky's physics is mistaken here. Thermal conductivity will govern both heat uptake and release.

36 Indeed, vitamin synthesis can depend on ultraviolet irridation. The sterol ergosterol (from ergot fungus, yeast), similar to cholesterol, is a precursor of vitamin D_2. Upon ultraviolet irradiation of ergosterol at a frequency of 282 nanometers, ergosterol is converted to *cis*-trachysterol. With further irradation, *cis*-trachysterol is converted into calciferol (vitamin D_2). When a cholesterol derivative 7-dehydrocholesterol (5,7-cholestadiene-3b-ol) is irradiated, it forms vitamin D_3, an even more potent form of the D vitamin. D vitamins can be considered to have a considerable biogeochemical importance, as they are required for the regulation of deposition of skeletal and dental calcium (Brown, 1975).

37 To maintain temperatures at which photosynthesis can occur.

38 Here Vernadsky is making a very clear distinction between living matter and the non-living matter of the biosphere. This may be compared to the Treviranian concept of "matter capable of life" (Driesch, 1914). Contrast this view with that of Hypersea theory (see McMenamin and McMenamin, 1994), where living matter and the biospheric living environment are one and the same, cutting out the bio-inert component.

* The domain of phenomena within an organism ("the field of living matter") is different, thermodynamically and chemically, from "the field of the biosphere".

[Editor's note: The manuscript upon which this translation is based carried 28 footnotes by Vernadsky. These are indicated, as here, by an * (or †). All other numbered footnotes are annotations by M. McMenamin (or I.A. Perelman, as noted)].

39 Here again, Vernadsky challenges (without citing) Oparin and Haldane, among others.

40 As put forth by A. I. Oparin (Fox, 1965), "[At] the dawn of European civilization, with the Greek philosophers, there were two clear tendencies in this problem. Those are the Platonic and the Democritian trends, either the view that dead matter was made alive by some spiritual principle or the assumption of a spontaneous generation from that matter, from dead or inert matter.

"The Platonic view has predominated for centuries and, in fact, still continues to exist in the views of vitalists and neo-vitalists."

"The Democritian line was pushed in the background and came into full force only in the seventeenth century in the work of Descartes. Both points of view really differed only in their interpretation of origin, but both of them equally assumed the possibility of spontaneous generation."

izations, by means of which we construct a unified theory of the cosmos. The character of such representations makes them unfruitful when their contents are introduced into the scientific domain.

Mechanistic representations, that on the other hand see merely the simple play of physico-chemical forces in living organisms, are equally fatal to progress in science. They hinder scientific research by limiting its final results; by introducing conjectural constructs based on guesswork,[41] they obscure scientific understanding. Successful conjectures of this sort would rapidly remove all obstacles from the progress of science, but conjectural constructs based on guesswork and their implementation has been linked too closely to abstract philosophical constructs that are foreign to the reality studied by science. These constructs have led to oversimplified analytical approaches, and have thus destroyed the notion of complexity of phenomena.[42] Conjectural constructs based on guesswork have not, thus far, advanced our comprehension of life.

We regard the growing tendency in scientific research to disclaim both these explanations of life, and to study living phenomena by purely empirical processes, as well-founded. This tendency or method acknowledges the impossibility of explaining life, of assigning it a place in our abstract cosmos, the edifice that science has constructed from models and hypotheses.

At the present time, we can approach the phenomena of life successfully only in an empirical fashion, that is, without making unfounded hypotheses. Only in this way can we discover new aspects of living phenomena that will enlarge the known field of physico-chemical forces, or introduce a new principle, axiom, or idea about the structure of our scientific universe. It will be impossible to prove these new principles or notions conclusively, or to deduce them from known axioms, but they will enable us to develop new hypotheses that relate living phenomena to our view of the cosmos, just as understanding of radioactivity connected the view of the cosmos to the world of atoms.

14 The living organism of the biosphere should now be studied empirically, as a particular body that cannot be entirely reduced to known physico-chemical systems. Whether it can be so reduced in the future is not yet clear.[43] It does not seem impossible, but we must not forget another possibility when taking an empirical approach—perhaps this problem, which has been posed by so many learned men of science, is purely illusory.

41 For notes on translation of this passage, see "Editor's Note on Translation and Transliteration."

42 Vernadsky is here challenging simplistic, mechanistic extrapolations in science and in so doing rightly challenges the extensions made of Cartesian- Newtonian mechanics to more complex classes of phenomena. As did Henri Poincaré some decades before, Vernadsky anticipates the problems that chaos theory presents to simple, extrapolation-based mechanistic explanations of phenomena. Vernadsky's intuition is reliable here—recognition of the complexity of the biosphere implies that he had at least an implicit sense of the feedback (cybernetic) dimensions of this field of study, although the language to express these concepts was not developed until shortly after Vernadsky's death. The word cybernetics, from the Greek *kybernetes*, "helmsman," was coined in 1948 by Norbert Wiener.

43 This might seem to make Vernadsky the arch holist (as opposed to reductionist). However, his main point here is that there are probably classes of phenomena that are neither easily nor well explained by inappropriately reductive scientific approaches. Vernadsky's insight on this subject has been decisively vindicated (Mikhailovskii, 1988; Progogine and Stengers, 1988). This makes Vernadsky's scientific approach quite unusual from a Western scientific perspective, for he is a confirmed empiricist who recognizes that holistic approaches will be required to study certain complex entities. His then is not a naïve empiricism, but a sophisticated empiricism in which an empirical approach is utilized to synthesize a scientifically realistic, holistic view of the subject under study. Similar approaches can be identified in the work of the Russian founders of symbiogenesis (Khakhina, 1988; Khakhina, 1992).

Analogous doubts, regarding the governance of all living forms by the laws of physics and chemistry as currently understood, often arise in the field of biology as well.

Even more so than in biology, in the geological sciences we must stay on purely empirical ground, scrupulously avoiding mechanistic and vitalistic constructs. Geochemistry is an especially important case, since living matter and masses of organisms are its principal agents, and it confronts us with living phenomena at every step.

Living matter gives the biosphere an extraordinary character, unique[44] in the universe. Two distinct types of matter, inert[45] and living, though separated by the impassable gulf of their geological history, exert a reciprocal action upon one another. It has never been doubted that these different types of biospheric matter belong to separate categories of phenomena, and cannot be reduced to one. This apparently-permanent difference between living and inert matter can be considered an axiom which may, at some time, be fully established.* Though presently unprovable, this principle must be taken as one of the greatest generalizations of the natural sciences.

The importance of such a generalization, and of most empirical generalizations in science, is often overlooked. The influence of habit and philosophical constructions causes us to mistake them for scientific hypotheses. When dealing with living phenomena, it is particularly important to avoid this deeply-rooted and pernicious habit.

15 There is a great difference between empirical generalizations and scientific hypotheses. They offer quite different degrees of precision. In both cases, we use deductions to reach conclusions, which then are verified by study of real phenomena. In a historical science like geology, verification takes place through scientific observation.

The two cases are different because an empirical generalization is founded on facts collected as part of an inductive research program. *Such a generalization does not go beyond the factual limits, and disregards agreements between the conclusions reached and our representations of nature.* There is no difference, in this respect, between an empirical generalization and a scientifically established fact. Their mutual agreement with our view of nature is not what interests us here, but rather the contradictions between them. Any such contradictions would constitute a *scientific discovery*.

44 So far as we know.

45 Inert matter as used here represents the raw matter, the raw materials of life. Although Vernadsky emphasizes his view that living organisms have never been produced by inert matter, he paradoxically implies that non-living stuff is in some sense alive, or at least has latent life. This should not be confused with any type of mysterious vital force, however; Vernadsky eschewed metaphysical interpretations. He was examining the idea that life has special properties, as old as matter itself, that somehow separated it from ordinary matter (into which it can, by dying, be transformed). Life can expand its realm into inert matter but it was not formed from "nothing."

* The change presently taking place in our ideas regarding mathematical axioms should influence the interpretation of axioms in the natural sciences; the latter have been less thoroughly examined by critical philosophical thought and would constitute a *scientific discovery*.

Certain characteristics of the phenomena studied are of primary importance to empirical generalizations; nevertheless, the influence of all the other characteristics is always felt. An empirical generalization may be a part of science for a long time without being buttressed by any hypothesis. As such, the empirical generalization remains incomprehensible, while still exerting an immense and beneficial effect on our understanding of nature.

But when the moment arrives, and a new light illuminates this generalization, it becomes a domain for the creation of scientific hypotheses, begins to transform our outlines of the universe, and undergoes changes in its turn. Then, one often finds that the empirical generalization did not really contain what was supposed, or perhaps, that its contents were much richer. A striking example is the history of D. J. Mendeleev's great generalization (1869) of the periodic system of chemical elements, which became an extended field for scientific hypothesis after Moseley's discovery[46] in 1915.

16 A hypothesis, or theoretical construction, is fashioned in an entirely different way. A single or small number of the essential properties of a phenomenon are considered, the rest being ignored, and on this basis, a representation of the phenomenon is made. A scientific hypothesis always goes beyond (frequently, far beyond) the facts upon which it is based.[47] To obtain the necessary solidity, it must then form all possible connections with other dominant theoretical constructions of nature, and *it must not contradict them.*[48]

An Empirical Generalization Requires No Verification After It Has been Deduced Precisely from the Facts.

17 The exposition we shall present is based only upon empirical generalizations that are supported by all of the known facts, and not by hypotheses or theories. The following are our beginning principles:

1. During all geological periods (including the present one) there has never been any trace of abiogenesis (direct creation of a living organism from inert matter).
2. Throughout geological time, no azoic (i.e., devoid of life) geological periods have ever been observed.[49]
3. From this follows:
   - **a)** contemporary living matter is connected by a genetic link to the living matter of all former geological epochs; and
   - **b)** the conditions of the terrestrial environment during all this time have favored the existence of living matter, and conditions have always been approximately what they are today.
4. In all geological periods, the chemical influence of living matter on the surrounding environment has not changed significantly; the same processes of superficial weathering have functioned on the Earth's surface during this whole time, and the average chemical compositions of both living matter and the Earth's crust have been approximately the same as they are today.
5. From the unchanging processes of superficial weathering, it follows that the number of atoms bound together by life is unchanged; the global mass of living matter has been almost constant throughout geological time.[50] Indications exist only of slight oscillations about the fixed average.
6. Whichever phenomenon one considers, the energy liberated by organisms is principally (and perhaps entirely) solar radiation. Organisms are the intermediaries in the regulation of the chemistry of the crust by solar energy.

18 These empirical generalizations force us to conclude that many problems facing science, chiefly philosophical ones, do not belong in our investigative domain, since they are not derived from empirical generalizations and require hypotheses for their formulation. For example, consider problems relating to the beginning of life on Earth (if there was a beginning[51]). Among these are cosmogonic models, both of a lifeless era in the Earth's past, and also of abiogenesis during some hypothetical cosmic period.

Such problems are so closely connected with dominant scientific and philosophical viewpoints and cosmogonic hypotheses that their logical necessity usually goes unquestioned. But the history of science indicates that these problems originate outside science, in the realms of religion and philosophy. This becomes obvious when these problems are compared with rigorously established facts and empirical generalizations — the true domain of science. These scientific facts would remain unchanged, even if the problems of biogenesis were resolved by negation, and we were to decide that life had always existed, that no living organism had ever originated from inert matter, and that azoic periods had never existed on Earth. One would be required merely to replace the present cosmogonic hypotheses by new ones, and to apply new scientific and mathematical

46 Actually it was 1913. British physicist H. Moseley studied x-rays emitted by different elements and found that the frequencies in the x-ray spectrum at which the highest intensities occurred varied with the element being studied. In other words, each element has a distinctive x-ray emission 'fingerprint'. This relationship established that the order number of an element in Mendeleev's periodic table (Fersman, 1946) could be established experimentally, and furthermore provided a foolproof method for demonstrating whether or not all the elements of a given region of the table had yet been discovered (Masterton and Slowinski, 1966). These discoveries formed the basis of x-ray energy dispersive (EDS) and wavelength dispersive analytical technology. EDS is frequently used in conjuction with the scanning electron microscope, since the imaging electron beam shot from the tungsten filament in a scanning electron microscope causes the elements in the sample being magnified to radiate their characteristic x-rays. These x-rays are collected by a detector and analysed, thus allowing elemental characterization of specimens being imaged by the scanning electron microscope.

47 It is this extrapolationistic aspect of scientific hypotheses that Vernadsky finds so objectionable.

48 And is far too deductive, in Vernadsky's view, to be the foundation of a reliable scientific methodology. We thus see the profound difference between Western (extrapolations, predictions) and Russian science (assertive scientific generalizations).

49 Again Vernadsky returns to this Huttonesque theme. He really cannot conceive of an azoic Earth. Elsewhere, however, he does admit (Vernadsky, 1939) the possibility that the abiogeneticists could be right (but without ever citing Oparin):

"We cannot shut our eyes, however, to the fact that Pasteur was possibly right, when contemplating in the investigation of these phenomena a way towards the solution of the most important biological problem, and seeking in them the possibility of creation of life on our planet."

Alexei M. Ghilarov (1995) attributes (p. 197) Vernadsky's views on abiogenesis to his overwhelming empiricism:

"Vernadsky claims that the problem of the origin of life cannot be considered in the framework of empirical science because we know nothing about geological layers that undoubtedly date back to a time when life on the Earth was absent."

In this vein, Vernadsky was fond of citing Redi's Principle of 1669 — *omne vivum e vivo* — "all the living are born from the living" (Vernadsky, 1923, p. 39).

A. Lapo adds here that in 1931 (Lapo, 1980, p. 279) Vernadsky wrote that Redi's principle does not absolutely deny abiogenesis — it only indicates the limits within which abiogenesis does not occur. It is possible that at some time early in Earth's history chemical conditions or states existed on Earth's crust, which are now absent, but which at the time were sufficient for the spontaneous generation of life.

50 This idea of Vernadsky's was controversial even before the 1920's, as pointed out (p. 22) by Yanshin and Yanshina (1988). They note that Vernadsky felt that throughout biological evolution, the forms of living matter had changed but the overall volume and weight of living matter had not changed through time. Convincing proof to the contrary was already available in 1912, when Belgian paleontologist Louis Dollo demonstrated the spread of life from shallow marine waters into oceanic depths and, later, on to land. Vernadsky's error here seems to be a result of the fact that he is completely in the thrall of his slavic variant of substantive uniformitarianism, "the more things change, the more they stay the same." Charles Lyell's western version of extreme substantive uniformitarianism holds that all creatures, including mammals, were present on Earth at a very early time. The Russian version holds biomass as an oscillating constant value through the vastness of geologic time. Dianna McMenamin and I show how the now-recognized increase in biomass over time is a consequence of what Vernadsky elsewhere calls the "pressure of life" (McMenamin and McMenamin 1994). Thus, abandonment of this untenable uniformitarian viewpoint regarding the constancy through geologic time of global biomass does not fundamen-

scrutiny to certain philosophical and religious viewpoints called into question by advances in scientific thought. This has happened before in modern cosmogony.

Living Matter in the Biosphere

19 Life exists only in the biosphere; organisms are found only in the thin outer layer of the Earth's crust, and are always separated from the surrounding inert matter by a clear and firm boundary. Living organisms have never been produced by inert matter. In its life, its death, and its decomposition an organism circulates its atoms through the biosphere over and over again, but living matter is always generated from life itself.

A considerable portion of the atoms in the Earth's surface are united in life, and these are in perpetual motion. Millions of diverse compounds are constantly being created, in a process that has been continuing, essentially unchanged, since the early Archean, four billion years ago.[52]

Because no chemical force on Earth is more constant than living organisms taken in aggregate, none is more powerful in the long run. The more we learn, the more convinced we become that biospheric chemical phenomena never occur independent of life.

All geological history supports this view. The oldest Archean beds furnish indirect indications of the existence of life; ancient Proterozoic rocks, and perhaps even Archean rocks,[53] have preserved actual fossil remains of organisms. Scholars such as C. Schuchert[54] were correct in relating Archean rocks to Paleozoic, Mesozoic, and Cenozoic rocks rich in life. Archean rocks correspond to the oldest-known accessible parts of the crust, and contain evidence that life existed in remotest antiquity at least 1.5 billion years ago.[55] Therefore the sun's energy cannot have changed noticeably since that time; this deduction[56] is confirmed by the convincing astronomical conjectures of Harlow Shapley.[57]

20 It is evident that if life were to cease the great chemical processes connected with it would disappear, both from the biosphere and probably also from the crust. All minerals in the upper crust—the free alumino-silicious acids (clays), the carbonates (limestones and dolomites), the hydrated oxides of iron and aluminum (limonites and bauxites), as well as hundreds of others, are continuously created by the influence of life. In the absence of life, the elements in these minerals would immedi-

tally weaken Vernadsky's other main arguments.

51 This is perhaps the most extreme articulation yet of Vernadsky's substantive uniformitarianism.

52 A. Lapo notes (written communication) that Russian geochemist A. I. Perelman suggested that the following generalization should be called "Vernadsky's Law": "The migration of chemical elements in the biosphere is accomplished either with the direct participation of living matter (biogenic migration) or it proceeds in a medium where the specific geochemical features (oxygen, carbon dioxide, hydrogen sulfide, etc.) are conditioned by living matter, by both that part inhabiting the given system at present and that part that has been acting on the Earth throughout geological history" (Perelman, 1979, p. 215).

53 See Pompeckj, 1928. Indeed as Vernadsky suggests, fossils of microorganisms are now known from Archean rocks.

54 See Schuchert, 1924.

55 Evidence for life is now thought to extend back to 3,800 million years ago; see Mojzsis, Arrhenius, McKeegan, Harrison, Nutman and Friend, 1996; and Hayes, 1996.

56 Now known to be false; the early sun is now thought to have been fainter than today, and yet the planetary surface was paradoxically warmer because of a larger proportion of greenhouse gases (principally carbon dioxide) in the atmosphere.

57 See Shapley, 1927.

ately form new chemical groups corresponding to the new conditions. Their previous mineral forms would disappear permanently, and there would be no energy in the Earth's crust capable of continuous generation of new chemical compounds.[58]

A stable equilibrium, a chemical calm, would be permanently established, troubled from time to time only by the appearance of matter from the depths of the Earth at certain points (e.g., emanations of gas, thermal springs, and volcanic eruptions). But this freshly-appearing matter would, relatively quickly, adopt[59] and maintain the stable molecular forms consistent with the lifeless conditions of the Earth's crust.

Although there are thousands of outlets for matter that arise from the depths of the Earth, they are lost in the immensity of the Earth's surface; and even recurrent processes such as volcanic eruptions are imperceptible, in the infinity of terrestrial time.

After the disappearance of life, changes in terrestrial tectonics would slowly occur on the Earth's surface. The time scale would be quite different from the years and centuries we experience. Change would be perceptible only in the scale of cosmic time, like radioactive alterations of atomic systems.

The incessant forces in the biosphere—the sun's heat and the chemical action of water—would scarcely alter the picture, because the extinction of life would result in the disappearance of free oxygen, and a marked reduction of carbonic acid.[60] The chief agents in the alteration of the surface, which under present conditions are constantly absorbed by the inert matter of the biosphere and replaced in equal quantity by living matter, would therefore disappear.

Water is a powerful chemical agent under the thermodynamic conditions of the biosphere, because life processes cause this "natural" *vadose* water[61] (§89) to be rich in chemically active foci, especially microscopic organisms. Such water is altered by the oxygen and carbonic acid dissolved within it. Without these constituents, it is chemically inert at the prevailing temperatures and pressures of the biosphere. In an inert, gaseous environment, the face of the Earth would become as immobile and chemically passive as that of the moon, or the metallic meteorites and cosmic dust particles that fall upon us.

21 Life is, thus, potently and continuously disturbing the chemical inertia on the surface of our planet. It creates the colors and forms of nature, the associations of animals and plants, and the

58 Here Vernadsky strongly anticipates some of the arguments made later by J. Lovelock, especially the thought that in an abiotic Earth the diatomic nitrogen and oxygen gases will combine to form nitrogen-oxygen compounds (NO_x); Williams, 1997.

59 See Germanov and Melkanovitskaya, 1975.

60 According to A. I. Perelman, the most recent data show that significant amounts of CO_2 are emitted during volcanic eruptions. Evidently, it is no accident that the significance of carbonate deposits abruptly increased after epochs of growing volcanic activity (for example, the Carbonaceous, Jurassic, Paleogene). Note, however, that in the event of the disappearance of life, the atmospheric concentration of CO_2 would rise, while there would be a sharp drop in the percent of carbonate deposits. Indeed, the concentrations of carbon dioxide in the atmospheres of Venus and Mars are very similar (965,000 and 953,000 parts per million volume, respectively), whereas that of Earth is dramatically less (350 parts per million volume; see Williams, 1997, p.110).

61 Vadose water is suspended water in soil or suspended in fragmented rock (regolith), above the level of groundwater saturation. Vernadsky here again demonstrates his marvelous insight, as well as his debt to Dokuchaev (his eacher), as he elucidates the biogeochemical importance of this microbe-rich, high surface-area environment.

creative labor of civilized humanity, and also becomes a part of the diverse chemical processes of the Earth's crust. There is no substantial chemical equilibrium on the crust in which the influence of life is not evident, and in which chemistry does not display life's work.

Life is, therefore, not an external or accidental phenomenon of the Earth's crust. It is closely bound to the structure of the crust, forms part of its mechanism, and fulfills functions of prime importance to the existence of this mechanism. Without life, the crustal mechanism of the Earth would not exist.

22 All living matter can be regarded as a single entity in the mechanism of the biosphere, but only one part of life, *green vegetation*, the carrier of chlorophyll, makes direct use of solar radiation. Through photosynthesis, chlorophyll produces chemical compounds that, following the death of the organism of which they are part, are unstable in the biosphere's thermodynamic field.

The whole living world is connected to this green part of life by a direct and unbreakable link.[62] The matter of animals and plants that do not contain chlorophyll has developed from the chemical compounds produced by green life. One possible exception might be autotrophic bacteria, but even these bacteria are in some way connected to green plants by a genetic link in their past. We can therefore consider this part of living nature as a development that came after the transformation of solar energy into active planetary forces. Animals and fungi accumulate nitrogen-rich substances which, as centers of chemical free energy, become even more powerful agents of change. Their energy is also released through decomposition when, after death, they leave the thermodynamic field in which they were stable, and enter the thermodynamic field of the biosphere.

Living matter — the totality of living organisms (§160) — is therefore a unique system, which accumulates chemical free energy in the biosphere by the transformation of solar radiation.

23 Studies of the morphology and ecology of green organisms long ago made it clear that these organisms were adapted, from their very beginning, to this cosmic function. The distinguished Austrian botanist I. Wiesner delved into this problem, and remarked, some time ago,[63] that light, even more than heat, exerted a powerful action on the form of green plants . . . "one

62 A partial exception to this general rule was discovered in 1977, the hydrothermal vent biotas of the active volcanic centers of mid-oceanic sea floor spreading ridges (Dover, 1996; Zimmer, 1996). The biotas here are dependent on hydrogen sulfide (normally poisonous to animals) emanating from the volcanic fissures, black smokers and white smokers. Chemosymbiotic bacteria within the tissues of vent biota animals, such as the giant clams and giant tube worms (vestimentiferan pogonophorans), not only detoxify the hydrogen sulfide but utilize it as an energy source in lieu of sunlight. Consider, however, the following from p. 290 of Yanshin and Yanshina (1988):

"Vernadsky considered that the stratified part of the earth's crust (or the lithosphere, as geologists call it) represents a vestige of bygone biospheres, and in that event the granite gneiss stratum was formed as a result of metamorphism and remelting of rocks originating at some point in time under the influence of living matter. Only basalts and other basic magmatic rocks did he regard as deep-seated and not connected genetically with the biosphere." [Although here the connection with the biosphere may simply be a longer period one .–M. McMenamin]

The melting (associated in this case with lithospheric and mantle pressure changes) and eruption of molten rock is probably responsible for exhalation most of the hydrogen sulfide released at mid-ocean ridges. Thus, even with regard to the energy source of the hydrothermal vent biotas (and the incredibly rapid growth of animals living there; see Lutz, 1994,), we may still be considering what is a part of the biosphere *sensu strictu* Vernadsky (E. I. Kolchinsky, 1987; Grinevald, 1996).

63 See Wiesner, 1877.

could say that light molded their shapes as though they were a plastic material."

An empirical generalization of the first magnitude arises at this juncture, and calls attention to opposing viewpoints between which it is, at present, impossible to choose. On the one hand, we try to explain the above phenomenon by invoking internal causes belonging to the living organism, assuming for example that the organism adapts so as to collect all the luminous energy of solar radiation.[64] On the other hand, the explanation is sought outside the organism in solar radiation, in which case the illuminated green organism is treated as an inert mass. In future work the solution should probably be sought in a combination of both approaches. For the time being the empirical generalization[65] itself is far more important.

The firm connection between solar radiation and the world of verdant creatures is demonstrated by the empirical observation that conditions ensure that this radiation will always encounter a green plant to transform the energy it carries. Normally, the energy of all the sun's rays will be transformed. This transformation of energy can be considered as *a property* of living matter, its *function* in the biosphere. If a green plant is unable to fulfill its proper function, one must find an explanation for this abnormal case.[66]

An essential deduction, drawn from observation, is that this process is absolutely automatic. It recovers from disturbance without the assistance of any agents, other than luminous solar radiation and green plants adapted for this purpose by specific living structures and forms. Such a re-establishment of equilibrium can only be produced in cases of opposing forces of great magnitude. The re-establishment of equilibrium is also linked to the passage of time.

24 Observation of nature gives indications of this mechanism in the biosphere. Let us reflect upon its grandeur and meaning. Land surfaces of the Earth are entirely covered by green vegetation. Desert areas are an exception, but they are lost in the whole.[67] Seen from space, the land of the Earth should appear green, because the green apparatus which traps and transforms radiation is spread over the globe, as continuously as the current of solar light that falls upon it.

Living matter — organisms taken as a whole — is spread over the entire surface of the Earth in a manner analogous to a gas; it produces a specific pressure[68] in the surrounding environment,

64 In this passage, in which he describes the need to capture light as influencing the morphology of photosynthetic organisms, Vernadsky (following Wiesner) anticipates the research results of both Adolf Seilacher (1985) and Mark McMenamin (1986). The empirical generalization Vernadsky describes here is simply that light influences the shapes of photosynthetic organisms. Either they adapt to maximize light capture, or the light somehow molds the shape of the organisms. The latter suggestion may sound odd but a very similar sentiment was expressed by D'Arcy Wentworth Thompson (1952). In his view, the physical and geometrical contraints of the environment evoke particular shapes from organisms as they evolve, and the array of possible shapes is finite.

65 That is, Wiesner's inference that light molds plant form.

66 As for instance in the achlorophyllous Indian Pipe *Monotropa*, which is nourished by linkages to a subterranean network of mycorrhizal mycelia.

67 In fact, desert areas are clearly identifiable from space.

68 Here Vernadsky introduces his concept of the "pressure of life." He phrased it succinctly in 1939 (see p. 13) as follows:

"The spreading of life in the biosphere goes on by way of reproduction which exercises a pressure on the surrounding medium and controls the biogenic migration of atoms. It is absent in . . . *inert substance*. The reproduction creates in the biosphere an accumulation of free energy which may be called *biogeochemical energy*. It can be precisely measured."

either avoiding the obstacles on its upward path, or overcoming them. In the course of time, living matter clothes the whole terrestrial globe with a continuous envelope,[69] which is absent only when some external force interferes with its encompassing movement....

This movement is caused by the *multiplication of organisms*, which takes place without interruption,[70] and with a specific intensity related to that of the solar radiation.

In spite of the extreme variability of life, the phenomena of reproduction, growth, and transformation of solar energy into terrestrial chemical energy are subject to fixed mathematical laws. The precision, rhythm, and harmony that are familiar in the movements of celestial bodies can be perceived in these systems of atoms and energy.

The Multiplication of Organisms and Geochemical Energy in Living Matter

25 The diffusion of living matter *by multiplication*, a characteristic of all living matter, is the most important manifestation of life in the biosphere and is the essential feature by which we distinguish life from death. It is a means by which the energy of life unifies the biosphere. It becomes apparent through the *ubiquity of life*, which occupies all free space if no insurmountable obstacles are met. The whole surface of the planet is the domain of life, and if any part should become barren, it would soon be reoccupied by living things. In each geological period (representing only a brief interval in the planet's history), organisms have developed and adapted to conditions which were initially fatal to them. Thus, the limits of life seem to expand with geological time (§119, 122). In any event, during the entirety of geological history life has tended to take possession of, and utilize, all possible space.

This tendency of life is clearly inherent; it is not an indication of an external force, such as is seen, for example, in the dispersal of a heap of sand or a glacier by the force of gravity.

The diffusion of life is a sign of internal energy—of the chemical work life performs—and is analogous to the diffusion of a gas. It is caused, not by gravity, but by the separate energetic movements of its component particles. The diffusion of living matter on the planet's surface is an inevitable movement caused by new organisms, which derive from multiplication and occupy new places in the biosphere; this diffusion is the autonomous energy of life in the biosphere, and becomes known through the

69 See McMenamin and McMenamin, 1994, for examples of this tendency for life to expand its realm.

70 Compare this with the slogan (first pointed out to me by Andrei Lapo) of A. Huxley (1921): "Everything ought to increase and multiply as hard as it can."

transformation of chemical elements and the creation of new matter from them. We shall call this energy *the geochemical energy of life in the biosphere.*

26 The uninterrupted movement resulting from the multiplication of living organisms is executed with an inexorable and astonishing mathematical regularity, and is the most characteristic and essential trait of the biosphere. It occurs on the land surfaces, penetrates all of the hydrosphere, and can be observed in each level of the troposphere. It even penetrates the interior of living matter, itself, in the form of parasites.[71] Throughout myriads of years, it accomplishes a colossal geochemical labor, and provides a means for both the penetration and distribution of solar energy on our planet.

It thus not only transports matter, but also transmits energy. The transport of matter by multiplication thus becomes a process *sui generis*. It is not an ordinary, mechanical displacement of the Earth's surface matter, independent of the environment in which the movement occurs. The environment resists this movement, causing a friction analogous to that which arises in the motion of matter caused by forces of electrostatic attraction. But movement of life is connected with the environment in a deeper sense, since it can occur only through a gaseous exchange between the moving matter and the medium in which it moves. The more intense the exchange of gases, the more rapid the movement, and when the exchange of gases stops, the movement also stops. This exchange is the *breathing* of organisms; and, as we shall see, it exerts a strong, controlling influence on multiplication. Movement due to multiplication is therefore of great geochemical importance in the mechanisms of the biosphere and, like respiration, is a manifestation of solar radiation.

27 Although this movement is continually taking place around us, we hardly notice it, grasping only the general result that nature offers us—the beauty and diversity of form, color, and movement. We view the fields and forests with their flora and fauna, and the lakes, seas, and soil with their abundance of life, as though the movement did not exist. We see the static result of the dynamic equilibrium of these movements, but only rarely can we observe them directly.

Let us dwell then for a moment on some examples of this movement, the creator of living nature, which plays such an

71 Abundant parasites colonizing the tissues of other organisms on land are one of the key characteristics of the land biota.

essential yet invisible role. From time to time, we observe the disappearance of higher plant life from locally restricted areas. Forest fires, burning steppes, plowed or abandoned fields, newly-formed islands, solidified lava flows, land covered by volcanic dust or created by glaciers and fluvial basins, and new soil formed by lichens and mosses on rocks are all examples of phenomena that, for a time, create an absence of grass and trees in particular places. But this vacancy does not last; life quickly regains its rights, as green grasses, and then arboreal vegetation, reinhabit the area. The new vegetation enters partially from the outside, through seeds carried by the wind or by mobile organisms; but it also comes from the store of seeds lying latent in the soil, sometimes for centuries.

The development of vegetation in a disturbed environment clearly requires seeds, but even more critical is the geochemical energy of multiplication. The speed at which equilibrium is reestablished is a function of the transmission of geochemical energy of higher green plants.

The careful observer can witness this movement of life, and even sense its pressure,[72] when defending his fields and open spaces against it. In the impact of a forest on the steppe, or in a mass of lichens moving up from the tundra to stifle a forest,[73] we see the actual movement of solar energy being transformed into the chemical energy of our planet.

28 Arthropods (insects, ticks, mites, and spiders) form the principal part of animal living matter on land. In tropical and subtropical regions, the social insects — ants and termites — play the dominant role. The geochemical energy of their multiplication (§37), which occurs in a particular way,[74] is only slightly less than that of the higher green plants themselves.

In termitaries, out of tens and sometimes hundreds of thousands of individuals, only one is endowed with the power of reproduction. This is the queen mother, who lays eggs throughout her life without stopping, and can keep it up for ten years or more. The number of eggs she can lay amounts to millions — some queens have been said to lay sixty eggs per minute with the regularity of a clock ticking seconds.

Multiplication also occurs in swarms, when one part of a generation flies away, with a new queen mother, to a location outside the air space of the founder colony. Instinct serves, with mathematical exactness, for the preservation of eggs instantly carried off by workers, in the flight of swarms, and in the substitution of a new queen mother for the old one in case of untimely demise. Marvelously precise laws govern the average values of such quantities as the number of eggs, the frequency of swarms, the numbers of individuals in a swarm, the size and weight of individual insects, and the rate of multiplication of termites on the Earth's surface. These values in turn condition the rate of transmission of geochemical energy by termite motion and expansion. Knowing the numerical constants that define these quantities, we can assign an exact number to the pressure produced on the environment by termites.

This pressure is very high, as is well known by men required to protect their own food supply from termitaries. Had termites met no obstacles in their environment — especially, no opposing forms of life — they would have been able to invade and cover the entire surface of the biosphere in only a few years, an area of over 5×10^8 square kilometers.

29 Bacteria are unique among living things. Although they are the smallest organisms (10^{-4} to 10^{-5} cm in length), they have the greatest rate of reproduction and the greatest power of multiplication. Each divides many times in 24 hours, and the most prolific can divide 63-64 times in a day, with an average interval of only 22-23 minutes between divisions. The regularity of this division resembles that of a female termite laying eggs or a planet revolving around the sun.

Bacteria inhabit a liquid or semi-liquid environment, and are most frequently encountered in the hydrosphere; great quantities also live in soil, and within other organisms. With no environmental obstacles, they would be able to create huge quantities of the complex chemical compounds containing an immense amount of chemical energy, and would be able to do it with inconceivable speed. The energy of this reproduction is so prodigious that bacteria could cover the globe with a thin layer of their bodies in less than 36 hours. Green grass or insects would require several years, or in some cases, hundreds of days.

The oceans contain nearly spherical bacteria, with a volume of one cubic micron. A cubic centimeter could thus contain 10^{12} bacteria. At the rate of multiplication just mentioned, this number could be produced in about 12 hours,[75] starting from a single bacterium. Actually, bacteria always exist as populations rather than as isolated individuals, and would fill a cubic centimeter much more quickly.

The division process takes place at the speed mentioned when

72 Here Vernadsky injects a qualitative version of his concept of the "pressure of life."

73 Vernadsky makes a veiled reference to Kropotkin (1987) at the beginning of this sentence, and in the next phrase rejects the idyllic connotations of Kropotkin's "mutual aid" theory. Vernadsky's materialist leanings are quite apparent here. Although he never to my knowledge cites it directly, Vernadsky must have been exposed to symbiogenesis theory, for one of his professors was A. S. Famintsyn, founder of Russian plant physiology and one of the chief architects of symbiogenesis theory (Khakhina, 1992). Famintsyn is best known for demostration that photosynthesis can take place under artificial light (Yanshin and Yanshina, 1988; Yanshin and Yanshina, 1989).

74 That is to say, by cooperative breeding (eusociality).

75 Actually, 12-15 hours.

conditions are propitious. The bacterial rate of increase drops with temperature, and this drop in rate is precisely predictable.

Bacteria breathe by interaction with gases dissolved in water. A cubic centimeter of water will contain a number of gas molecules much smaller than Loschmidt's number (2.7×10^{19}), and the number of bacteria cannot exceed that of the gas molecules with which they are generatively connected. The multiplication of organized beings is, therefore, limited by respiration and the properties of the gaseous state of matter.

30 This example of bacteria points to another way of expressing the movement in the biosphere caused by multiplication. Imagine the period of the Earth's history when the oceans covered the whole planet. (This is simply a conjecture which was erroneously accepted by geologists). E. Suess[76] dates this "universal sea" or Panthalassa in the Archean Era. It was undoubtedly inhabited by bacteria, of which visible traces have been established in the earliest Paleozoic strata. The character of minerals belonging to Archean beds, and particularly their associations, establish with certainty the presence of bacteria in all the sediments which were lithified to form Archean strata, the oldest strata accessible to geological investigation. If the temperature of the universal sea had been favorable, and there had been no obstacles to multiplication, spherical bacteria (each 10^{-12} cc in volume) would have formed a continuous skin over the Earth's approximately 5.1×10^{8} square kilometers in less than thirty six hours.

Extensive films, formed by bacteria, are constantly observed in the biosphere. In the 1890's, Professor M. A. Egounov attempted to demonstrate[77] the existence of a film of sulfurous bacteria, on the boundary of the free oxygen surface[78] (at a depth of about 200 meters), covering an enormous surface area.[79] The research of Professor B. L. Isachenko,[80] performed on N. M. Knipkovitch's 1926 expedition,[81] did not confirm these results; but the phenomenon can nevertheless be observed, at a smaller scale, in other biogeochemically dynamic areas. An example is the junction between fresh and salt water in Lake Miortvoi (Dead Lake)[82] on Kildin Island, where the sediment-water interface is always covered by a continuous layer of purple bacteria.[83]

Other, somewhat larger microscopic organisms, such as plankton, provide a more obvious example of the same kind of phenomenon. Ocean plankton can rapidly create a film covering thousands of square kilometers.

76 See Suess, 1883-1909. This global sea is now called Mirovia.

77 See Egounov, 1897.

78 Also called the "oxygen minimum zone."

79 Based on the depth at which *Thioplaca* mats on the sea floor break up during the Austral winter off the modern coasts of Peru and Chile, storm wave base apparently occurs at 60 meters water depth (see Fossing, et.al., 1995). These mats can indeed be, as per M. A. Egounov's demonstration, of great lateral extent.

80 Boris L. Isachenko was a microbiologist who became heavily involved in the Vernadskian research program. His main interest was the propagation of microorganisms in nature and their role in geological processes, but he also did research in marine microbiology. In 1914 he made the first study of the microflora of the Arctic Ocean as part of a project that was subsequently extended to the Sea of Japan, the Baltic Sea, the Kara Sea, the Sea of Marmora, the Black Sea, the Caspian Sea, and the Sea of Azov. In 1927 he did research on salt-water lakes and medicinal muds. Isachenko also established the role of actinomyces in imparting an earthy odor to water (J. Scamardella, personal communication).

81 Nikolay M. Knipkovitch was a zoologist and ichthyologist. The world's first oceanographic vessel, the *Andrey Pervozvannyy*, was built for his oceanographic expeditions. The voyages of 1922-27 took place in the Sea of Azov and the Black Sea (J. Scamardella, personal communication).

82 Vernadsky was mistaken about the name of this lake: it is Lake Mogilnoe (Grave Lake) (A. Lapo, written communication).

83 See Deriugin, 1925. Vernadsky expressed dismay that the results of K. M. Deriugin's (1878-1936) famous expedition remained only partly published, and urged the Zoological Museum of the Academy of Science to fulfill its scientific and civic duty to fully publish these works (see Vernadsky, 1945, footnote 15).

The geochemical energy of these processes can be expressed as the speed of transmission of vital energy to the Earth's surface. This speed is proportional to the intensity of multiplication of the species under consideration. If the species were able to populate the entire surface of the Earth, its geochemical energy would have traversed the greatest possible distance; namely, a great circle of Earth (equal to the length of the equator).

If the bacteria of Fischer[84] were to form a film in Suess's Panthalassic ocean, the speed of transmission of their energy along a great circle would be approximately 33,000 cm/sec., the average speed of movement around the Earth resulting from multiplication starting with one bacterium, for which a complete "tour" of the globe would take slightly less than 36 hours.

The speed of transmission of life, over the maximum distance accessible to it, will be a characteristic constant for each type of homogenous living matter, specific for each species or breed. We shall use this constant to express the geochemical activity of life. It expresses a characteristic both of multiplication, and of the limits imposed by the dimensions and properties of the planet.

31 The speed of transmission of life is an expression not only of the properties of individual organisms, or the living matter of which they are composed, but also of their multiplication as a planetary phenomenon within the biosphere. The size of the planet is an integral part of any such considerations. The concept of *weight* provides an analogy: the weight of an organism on Earth would not be the same as it would be on Jupiter; similarly, the speeds of transmission of life on Earth would be different from the speed observed for the same organism on Jupiter, which has a different diameter.

32 While phenomena of multiplication have been too much neglected by biologists, certain almost unnoticed empirical generalizations about these phenomena have, by their repetition, come to seem obvious. Among these are the following:

1 *The multiplication of all organisms can be expressed in geometrical progressions.* Thus,

$2^{nD} = N_n$

where n is the number of days since the start of multiplication; D is the ratio of progression (the number of generations formed in 24 hours, in the case of unicellular organisms

84 See Fischer, 1900.

multiplying by division); and N_n is the number of individuals formed in n days. D will be characteristic for each homogenous type of living matter (or species). The process is considered infinite: no limits are placed upon n nor N_n in this formula.[85]

2 This potential for infinite growth is nevertheless constrained in the biosphere because *the diffusion of living matter is subject to the law of inertia.*[86] It can be accepted as empirically demonstrated that the process of multiplication is hindered only by external forces. It slows down at low temperatures, and weakens or ceases in the absence of food, of gas to breathe, or of space for the newly born.

In 1858, Darwin[87] and Wallace put this idea in a form familiar to older naturalists, such as C. Linnaeus,[88] G. L. L. Buffon,[89] A. Humboldt,[90] C. G.. Ehrenberg,[91] and K. E. Baer,[92] who had studied the same problem. *If not prevented by some external obstacle, each organism could cover the whole globe and create a posterity equal to the mass of the ocean or the Earth's crust or the planet itself, in a time that is different, but fixed, for each organism.*[93]

3 The specific time required for this is related to the organism's size; small and light organisms multiply more rapidly than large and heavy ones.

33 These three empirical principles portray the phenomenon of multiplication as it never actually occurs in nature, since life is in fact inseparable from the biosphere and its singular conditions. Corrections must be applied to the abstractions for time and space utilized in the above formula.

34 Limitations are imposed upon all quantities that govern the multiplication of organisms, including the maximum number that can be created (N_{max}), the geometrical progression ratio, and the speed of transmission of life. The limits will be determined by the physical properties of the medium in which life exists, and particularly, by the gaseous interchange between organisms and the medium, since organisms must live in a gaseous environment, or in a liquid containing dissolved gases.

35 The dimensions of the planet also impose limitations. The surfaces of small ponds are often covered by floating, green vegetation, commonly duckweed (various species of *Lemna*) in our latitudes. Duckweed may cover the surface in such a closely packed fashion that the leaves of the small plants touch each

85 In other words, the number of individuals of a population after a given number of days is equal to two raised to the power of the growth ratio (the number of generations in a day) times the number of days. The population thus increases rather quickly if the product of the growth ratio and the number of days is large.

86 This is directly analogous to the law of inertia in physics, e. g., a body in motion will remain in motion until acted upon by an external force.

87 Some orthodox practitioners of western-style science have expressed "unease with Darwinism" because it seemed tautological, in other words, difficult to falsify (Ruse, 1988, p. 10). From Vernadsky's point of view, Darwin and Wallace's discovery of natural selection was clearly an extenstion of earlier ideas. But Vernadsky would have been firmly set against the lofty position neo-darwinists have given the role of chance in their evolutionary schema. According (p. 197) to Alexei M. Ghilarov (1995):

"It is understandable, therefore, that despite all his respect for Darwin and Wallace, he considered their concept to be only a general theory of evolution (opposing creationism) rather than a fruitful hypothesis of the origin of species by natural selection. The ideas of stochastic variation, undirectedness, and unpredictability were alien views to Vernadsky" Recall Vernadsky's statement "chance does not exist".

88 See Linnaeus, 1759.

89 See Buffon, 1792.

90 See Humboldt, 1859.

91 See Ehrenberg, 1854.

92 See Baer, 1828, 1876.

93 Here, according to A. I. Perelman, no account is taken of the inner factors, the exhaustion of the capabilities of organisms of a particular species to undergo a final progressive development (compare this with Schindewolf's [translated 1993] concept of senescence), that might

other. Multiplication is hindered by lack of space, and can resume only when empty places are made on the water surface by external disturbances. The maximum number of duckweed plants on the water surface is obviously determined by their size, and once this maximum is reached, multiplication stops. A dynamic equilibrium, not unlike the evaporation of water from its surface, is established. The tension of water vapor and the pressure of life[94] are analogous.

Green algae provide a universally known example of the same process. Algae have a geochemical energy far higher than that of duckweed and, in favorable conditions, can cover the trunks of trees until no gaps are left (§50). Multiplication is arrested, but will resume at the first hint of available space in which to quarter new, individual protococci. The maximum number of individual algae that the surface of a tree can hold is, within a certain margin of error, rigorously fixed.

36 These considerations can be extended to the whole of living nature, although the carrying capacity varies over a wide range. For duckweed or unicellular protococci, it is determined solely by their size; other organisms require much larger surfaces or volumes. In India, the elephant demands up to 30 square kilometers; sheep in Scotland's mountain pastures require about 10,000 square meters; the average beehive needs a minimum of 10 to 15 square kilometers of leafy forest in the Ukraine (about 200 square meters for each bee); 3000 to 15,000 individual plankton typically inhabit a liter of water; 25 to 30 square centimeters is sufficient for ordinary grasses; a few square meters (sometimes up to tens of meters) is needed for individual forest trees.

It is evident that the speed of transmission of life depends on the normal *density* of living matter, an important constant of life in the biosphere.* Although this has been little-studied, it clearly applies to continuous layers of organisms, such as duckweed or *Protococcus*, and also applies to a volume completely filled by small bacteria. The concept can be extended to all organisms.

37 With respect to the limitation of multiplication imposed by the dimensions of the planet, *there is evidently a maximum fixed distance over which the transmission of life can take place*; namely, the length of the equator: 40,075,721 meters. If a species were to inhabit the whole of the Earth's surface at its maximum density, it would attain its maximum number of individuals. We

lead to organic multiplication of such species or families, in competition with other, more-progressive species or families. Inner factors of development have no less significance than external vigor. The position described by Vernadsky is, however, in agreement not only with the biological viewpoint of his times, but also with that which has prevailed until quite recently.

94 Vernadsky's "pressure of life" differs from Lamarck's 1802 concept of the "power of life" (*pouvoir de la vie*; see page 92 in Lamarck, 1964). Lamarck referred to the ability of life to keep living matter in the living state as a "force acting against the tendency of compounds to separate into their constituents" (A. V. Carozzi's footnote 13 in Lamarck, 1964). Vernadsky regards the pressure of life as if he were considering a gas obeying the laws of physics, particularly in its tendency to expand (Wentworth and Ladner, 1972).

Thus Vernadsky's pressurized, expansive properties of life contrast sharply with Lamarck's balancing power of life. Lamarck's view has geological antecedant in the work of Leonardo Da Vinci, who in Folio 36r of *Codex Leicester* described his hypothesis for the relatively constant level of sea water. Da Vinci, following lines of thought begun by Ristoro d'Arezzo, argued that the seas remain at a constant level, and Earth in balance, thanks to subterranean waters that erode Earth's interior, causing caverns to collapse. But for the collapse of caverns, sea water would sink into Earth (Farago, 1996). The collapses prevent the sea from draining completely.

By the seventeenth century the flow of water from cloud to ocean was better understood, leading Sachse de Lowenheimb in his 1664 *Oceanus Macro-microcosmos* to liken hydrospheric circulation to the circulation of blood in the human body.

* Vernadsky, 1926b.

95 For example, generations per day.

96 Vernadsky's derivation of biogeochemical constants, from V. I. Vernadsky, 1926c, is as follows:

Δ = optimal number of generations per day shall call this number (N_{max}) *the stationary number for homogenous living matter*. It corresponds to the maximum possible energy output of homogenous living matter—the maximum geochemical work—and is of great importance for evaluating the geochemical influence of life.

Each organism will reach this limiting number at a speed which is its speed of transmission of life, defined by the formula,

$$V = \frac{13963.3\ \Delta}{\log N_{max}}$$

If the speed of transmission V remains constant, then obviously the quantity D, which defines the intensity of multiplication[95] (§32), must diminish, as the number of individuals approaches the stationary number and the rate of multiplication slows down.[96]

38 This phenomenon was clearly enunciated 40 years ago by Karl Semper,[97] an accurate observer of living nature, who noted that the multiplication of organisms in small ponds diminished as the number of individuals increased. The stationary number is not actually attained, because the process slows down as the population increases, due to causes that may not be external. The experiments of R. Pearl and his collaborators on *Drosophila* and on fowls (1911-1912) confirm Semper's generalization in other environments.[98]

39 The speed of transmission of life conveys a vivid idea of the geochemical energy of different organisms. As we have seen, it varies widely with the size of the organism, from some 331 meters per second for bacteria (approximately the speed of sound in air), to less than a millimeter (0.9 mm) per second for the Indian elephant. The speeds of transmission of other organisms lie between these two extreme values.

40 In order to determine the energy of life, and the work it produces in the biosphere, both the mass and velocity (or speed of transmission) of the organism must be considered. *The kinetic geochemical energy of living matter* is expressed by the formula $PV^2/2$, where P is the average weight of the organism,* and V is the speed of transmission.

This formula makes it possible to determine the geochemical work that can be performed by a given species, whenever the surface or volume of the biosphere is known.

Attempts to find the geochemical energy of living matter per

k_1 = the greatest dimension (average value) of the organism in cm
V_1 = the velocity of bacteria

For bacteria, take
$\Delta = 64$, k_1 = 1 micron = .0001 cm.

Then:

$$V_1 = \frac{13963 \cdot \Delta}{18.71\ (\log_{10} k_1)}$$

$$V_1 = \frac{13963 \cdot (64)}{18.71 - (-4)}$$

V_1 = 39,349 cm/sec = .393 km/sec

(.393 km/sec)(5 sec)(.6214 miles/1 km) = 1.22 miles

Or, in other words, the velocity of bacteria on the surface of the planet works out to be about 1.22 miles in five seconds, assuming of course perfect survivorship of progeny and geometric rates of population increase (conditions which never actually occur in nature). The 13963 multiplier in the numerator of this formula is derived in footnote 19 of Vernadsky, 1989.

The velocity formula used in the above example can be explained as follows. This velocity formula has two forms:

The mean radius of Earth is 6.37 × 10^6 meters, and the surface area is equal to 5.099 × 10^{14} m^2 or 5.099 × 10^{18} cm^2. The base ten logarithm of this last number equals 18.707. So, comparing the denominators of the two velocity formulas above,

$$18.707 = \log_{10}(k_1) = \log_{10} N_{max}$$
$$18.707 = \log_{10} N_{max} + \log_{10}(k_1)$$
$$18.707 = \log_{10}(N_{max})(k_1)$$
$$10^{18.707} = (k_1)\ (\log_{10} N_{max})$$
$$N_{max} = \frac{10^{18.707}}{k_1}$$

Or, to put it differently, the maximum number of creatures equals their average maximum dimension divided into the surface area of Earth.

97 See for example Semper, 1881.

98 See Pearl, 1912; and Semper, 1881.

* The average weight of a species, P (the average weight of an element of homogenous living matter), logically should be replaced by the average number of atoms in an individual. In the absence of elementary chemical analysis of organisms, this can be calculated only in exceptional cases.

hectare[99] have been made for a long time; for example, in the estimates of *crops*. Facts and theory in this regard are incomplete, but important empirical generalizations have been made. One is that the quantity of organic matter per hectare is both: **1.** limited, and; **2.** intimately connected with the solar energy assimilated by green plants.

It seems that, in the case of maximum yield, the quantity of organic matter drawn from a hectare of soil is about the same as that produced in a hectare of ocean. The numbers are nearly the same in size, and tend to the same limit, even though soil consists of a layer only a few meters thick, while the life-bearing ocean region is measured in kilometers.[100] The fact that this nearly equal amount of vital energy is created by such different layers can be attributed to the illumination of both surfaces by solar radiation, and probably also to characteristic properties of soil. As we shall see, organisms that accumulate in the soil (microbes) possess such an immense geochemical energy (§155) that this thin soil layer has a geochemical effect comparable to that of the ocean, where the concentrations of life are diluted in a deep volume of water.

41 The kinetic geochemical energy $PV^2/2$, concentrated per hectare, may be expressed by the following formula:[101]

$$A_1 = \left(\frac{PV^2}{2}\right) \times \left(\frac{10^8}{K}\right) = \frac{(PV^2)\ (N_{max})}{2(5.10065 \times 10^{18})}$$

where $10^8/K$ is the maximum number of organisms per hectare (§37); K is the coefficient of density of life (§36); N_{max} is the stationary number for homogenous living matter (§37); and 5.10065 × 10^{18} is the area of the Earth in square centimeters. Characteristically, this quantity seems to be a constant for protozoa, for which the formula gives $A_1 = (PV^2/2) \times (10^8/K) = a \times (3.51 \times 10^{12})$ in CGS units. The coefficient a is approximately one.*

This formula shows that the kinetic geochemical energy is determined by the velocity V, and is thus related to the organism's weight, size, and intensity of multiplication. In relation to Δ, V can be expressed as

$$V = \frac{(46{,}383.93)\ (\log 2)\ (\Delta)}{18.70762 - \log K} \quad \text{[in CGS units]}^{\dagger},$$

in which the constants are related to the size of the Earth. The largest known value for V is 331 meters per second; and for Δ, about 63 divisions per day.[102]

This formula shows that the size of the planet, alone, cannot

99 A large quantity of corroborative data for natural vegetation is found in the book by Rodin and Basilevich, 1965.

100 Although the notion was important to Vernadsky (possibly because it demonstrated that the transformative power of life was as potent on land as in the sea), this assertion that land and sea biomass are roughly equal is not valid. Upward transport by vascular plants of fluid and nutrients allows the land biota to far outstrip the marine biota (by approximately two orders of magnitude) in terms of overall biomass. (McMenamin and McMenamin, 1993; McMenamin and McMenamin, 1994). Annual productivity on a per square meter basis is about four times greater on the land than in the sea.

101 This formula calculates the value A_1, the geochemical energy of a particular species of organism concentrated on a given patch of Earth's surface area. It is calculated by dividing the product of the geochemical energy of that species ($PV^2/2$) and its maximum abundance on Earth (N_{max}) by the surface area of Earth. The "2" in the denominator of the final quotient is from the denominator of $PV^2/2$. The calculation is an interesting and unusual way to describe the bioenergetics of organisms.

* Corresponding to the density of protozoan protoplasm, which, by recent measurements (see Leontiev, 1927), is about 1.05. The quicker the multiplication, the more intense the respiration.

† This expression V applies for all organisms, and not just for protozoans. For all other groups, such as higher animals and plants, the expression A_1 has another, *lesser* value, as a result of profound differences between the metabolism and organization of complex creatures (such as animals and plants) and unicellular protists. I cannot here delve into examination of these complex and important distinctions.

[Editor's note: This footnote appears in the 1989 edition but is cryptic because Vernadsky makes just such a comparison in sections to follow. Perhaps he meant that he did not account for the actual limits imposed upon V and Δ. Can these quantities attain higher values, or does the biosphere impose limits upon them?[103] An obstacle that imposes maximum values upon these constants does, in fact, exist; namely, the gaseous exchange that is essential for the life and multiplication of organisms.

42 Organisms cannot exist without exchange of gases—*respiration*—and the intensity of life can be judged by the rate of gaseous exchange.

On a global scale, we must look at the general result of respiration, rather than at the breathing of a single organism. The respiration of all living organisms must be recognized as part of the mechanism of the biosphere. There are some long-standing empirical generalizations in this area, which have not yet been sufficiently considered by scientists.

The first of these is that *the gases of the biosphere are identical to those created by the gaseous exchange of living organisms.* Only the following gases are found in noticeable quantities in the biosphere, namely oxygen, nitrogen, carbon dioxide, water, hydrogen, methane, and ammonia. This cannot be an accident. The free oxygen in the biosphere is created solely by *gaseous exchange in green plants,*[104] and is the principal source of the free chemical energy of the biosphere. Finally, *the quantity of free oxygen* in the biosphere, equal to 1.5×10^{21} grams (about 143 million tons[105]) is of the same order as the existing quantity of living matter,[106] independently estimated at 10^{20} to 10^{21} grams.[107] Such a close correspondence between terrestrial gases and life strongly suggests[108] that the breathing of organisms has primary importance in the gaseous system of the biosphere; in other words, *it must be a planetary phenomenon.*

43 The intensity of multiplication, and likewise the values of V and Δ, cannot exceed limits imposed by properties of gases, because they are determined by gaseous exchange. We have already shown (§29) that the number of organisms that can live in a cubic centimeter of any medium must be less than the number of molecules of gas it contains (Loschmidt's number; 2.716×10^{19} at standard temperature and pressure*). If the velocity V were greater than 331 meters per second, the number of organisms smaller than bacteria (i.e., with dimensions 10^{-5} centimeters or smaller) would exceed 10^{19} per cubic centimeter. Due to respiration, the number of organisms that exchange gas molecules would have to increase as their individual dimensions decreased. As their dimensions approached that of molecules, the speed would rise to improbable values and become physically absurd.

Breathing clearly controls the whole process of multiplication on the Earth's surface. It establishes mutual connections between the numbers of organisms of differing fecundity, and determines, in a manner analogous to temperature, the value of Δ that an organism of given dimensions can attain. Limitations to the ability to respire are the primary impediment to the attainment of maximum population density.

Within the biosphere, there is a desperate struggle among biospheric organisms, not only for food, but also for air; and the struggle for the latter is the more essential, for it controls multiplication. Thus respiration (or breathing) controls maximal possible geochemical energy transfer per hectare surface area.

44 On the scale of the biosphere, the effect of gaseous exchange and the multiplication it controls is immense. Inert matter exhibits nothing even remotely analogous, since any living matter can produce an unlimited quantity of new living matter.

The weight of the biosphere is not known, but it is certainly only a tiny fraction of the total weight of the Earth's crust (or even of the 16-20 kilometers that participate in geochemical cycles accessible to direct study) (§78). The weight of the top 16 kilometers is 2×10^{25} grams, but if there were no environmental obstacles, a much larger amount of living matter could be created by multiplication in a negligible span of geological time. The cholera vibrio and the bacterium *E. coli* could yield the above mass in 1.6 to 1.75 days. The green diatom *Nitzchia putrida*, a mixotrophic organism of marine slimes which consumes decomposed organic matter and also uses solar radiation in its chloroplasts, could produce 2×10^{25} grams in 24.5 days. (This is one of the fastest growing organisms, possibly because it utilizes already existing organic matter.)

The Indian elephant, having one of the slowest multiplication rates, could produce the same quantity of matter in 1300 years, a short moment in the scale of geological time. Further along the growth curve, of course, the elephant could produce the same mass in days.[109]

45 Obviously, no organism produces such quantities of matter in the real world. There is nothing fantastic, however, about dis-

intend to thoroughly elucidate the subject; Vernadsky, 1989].

102 This formula is derived in footnote 22 of Vernadsky, 1989. It is in a sense redundant; Vernadsky includes it as a demonstration, to confirm for readers that the speed of transmission of life (V) may be expressed as a function of the generations per day (Δ), the size of the organisms in question (K), *and* the dimensions of Earth.

103 Alexei M. Ghilarov (1995) had this (p. 200) to say about Vernadsky's calculation:

"Vernadsky claimed that the rate of natural increase and dispersal of any organism must be related to the area of the Earth's surface, to the length of the equator, to the duration of one rotation of the Earth on its axis, and other *planetary characteristics*. . . . Emphasizing that "all organisms live on the Earth in restricted space which is *of the same size* for all of them" Vernadsky . . . . simply implies that all organisms inhabit a common planet of a finite size [italics his]."

But Ghilarov misses the main point of Vernadsky's mathematical demonstration. For Vernadsky, the size of Earth is invariant. The main variables, which are constant for any species, are Δ (often expressed in generations per day) and K (the organism's size). So the only thing that truly varies, and thus determines the geochemical energy and the velocity or speed of transmission of life, is an organism's respiratory rate (the rate of exchange of gases in air or as dissolved gases in water). For Vernadsky, respiration is the key to understanding any species of organisms, for respiration is the fundamental process linking the organism to the rest of the biosphere. An organism's respiring surfaces represent the interface across which living matter and bio-inert matter interact.

104 In 1856 C. Koene [citation unknown] hypothesized that atmospheric oxygen was the result of photosynthesis. Vernadsky gave this idea special attention, and from the perspective of geochemistry (Voitkevich, Miroshnikov, Povarennykh, Prokhorov, 1970). The Keene hypothesis was accepted without much complaint since it was known that plants release oxygen (see Van Hise, 1904, p. 949; "it is suspected that a considerable percentage of the oxygen now in the atmosphere could be thus be accounted for" [i.e., by photosynthesis]), but Vernadsky was the first to demonstrate the biogenic origin of atmospheric oxygen in its global entirety (Vernadsky, 1935; see also Oparin, 1957, p. 157). For a discussion of the current status of the problem see Molchanov and Pazaev, 1996. [The citation for Koene, 1856, and few others noted in the text elsewhere, have not been located. If anyone reading this text is familiar with this or other unknown or incomplete citations noted, please provide the information to the publisher, Peter N. Nevraumont, Nevraumont Publishing Company, 16 East 23rd Street, New York, New York 10010, and it will be included in future editions.]

105 The current estimate for the mass of the atmosphere is 5×10^{24} grams. Multiplying this value by the weight percent of oxygen in the atmosphere (22.87% of atmospheric mass assuming 2% by volume water vapor in air; see Gross, 1982; and Levine, 1985) gives an atmospheric oxygen content of 1.143×10^{24} grams. Vernadsky's value is too low by at least three orders of magnitude. He must have badly underestimated the mass of the atmosphere.

106 It is difficult to verify or reject Vernadsky's assertion here. The total biomass of Earth is still poorly known, as a result of uncertainties as to the total biomass of subterranean bacteria.

107 According to recent data, the total biomass of Earth averages 7.5×10^{17} grams of organic carbon (Romankevich, 1988). Vernadsky apparently meant total biomass, whereas Romankevich's data include only organic carbon.

108 Because of the vast amount of free oxygen in the atmosphere.

*Microbes live in a gaseous environment having this number of molecules at 0° and 760 mm pressure. In the presence of bacteria, the number of gaseous molecules must be less. A cubic centimeter of liquid containing placements of mass of this order resulting from multiplication in the biosphere. Exceptionally large masses of organisms are actually observed in nature. There is no doubt that life creates matter at a rate several times greater than 10^{25} grams per year.[110] The biosphere's 10^{20} to 10^{21} grams of living matter is incessantly moving, decomposing, and reforming. The chief factor in this process is not growth, but multiplication. New generations, born at intervals ranging from tens of minutes to hundreds of years, renew the substances that have been incorporated into life.

Because enormous amounts of living matter are created and decomposed every 24 hours, the quantity which exists at any moment is but an insignificant fraction of the total created in a year.

It is hard for the mind to grasp the colossal amounts of living matter that are created, and that decompose, each day, in a vast dynamic equilibrium of death, birth, metabolism, and growth. Who can calculate the number of individuals continually being born and dying? It is more difficult than Archimedes' problem of counting grains of sand—how can they be counted when their number varies and grows with time? The number that exists, in a time brief by human standards, certainly exceeds the grains of sand in the sea by a factor of more than 10^{25}.

Photosynthetic Living Matter

46 The amount of living matter in the biosphere (10^{20} to 10^{21} grams) does not seem excessively large, when its power of multiplication and geochemical energy are considered.

All this matter is generatively connected with the living green organisms that capture the sun's energy. The current state of knowledge does not allow us to calculate the fraction of all living matter that consists of green plants, but estimates can be made. While it is not certain that green living matter predominates on the Earth as a whole, it does seem to do so on land.[111] It is generally accepted that animal life predominates (in volume) in the ocean. But even if heterotrophic animal life should be found to be the greater part of all living matter, its predominance cannot be large.

Are the two parts of living matter—photoautotrophic and heterotrophic—nearly equal in weight? This question cannot now be answered,[112] but it can be said that estimates of the weight of green matter, alone, give values of 10^{20} to 10^{21} grams, which are the same in order of magnitude as estimates for living matter *in toto*.

microbes must contain fewer than 10^{19} molecules; it cannot at the same time contain a like number of microbes.

109 An interesting comparison (suggested by Peter N. Nevraumont) may be made between Vernadsky's and Darwin's interpretation of the rate of increase of elephants, the slowest breeding animals. Whereas Vernadsky emphasized the biogeological accumulation of a quantity of elephant "matter," Darwin emphasized the geometrical rate of increase in the number of individual elephants in the struggle for existence, calculating that within 740-750 years a single breeding female could theoretically produce nineteen million offspring (Darwin, 1963, p.51).

110 Recent calculations show the total biomass production of Earth averages 1.2×10^{17} grams of organic carbon per year (Romankevich, 1988; Schlesinger 1991). In energetic terms, solar energy is fixed in plants by photsynthesis at a net rate of about 133 TW (10^{12} W; see Lovins, Lovins, Krause, and Bach, 1981).

111 On land, the total biomass of autotrophs is nearly a hundred times as large as the biomass of heterotrophs (738×10^{15} versus 8.10×10^{15}, respectively). See Romankevich, 1988.

112 The present answer to this question would be "no." Total photoautotrophic biomass on Earth is 740×10^{15} grams of organic carbon, whereas total heterotrophic biomass is only about 10×10^{15} grams of organic carbon. See Romankevich, 1988; and Schlesinger 1991.

47 Solar energy transformers on land are structured quite differently from those in the sea. On dry land, phanerogamous,[113] herbaceous plants predominate. Trees probably represent the greatest fraction, by weight, of this vegetation; green algae and other cryptogamous plants (principally protista) represent the smallest fraction. In the ocean, microscopic, unicellular green organisms predominate; grasses like *Zostera* and large algae constitute a smaller portion of green vegetation, and are concentrated along shores in shallow areas accessible to sunlight. Floating masses of them, like those in the Sargasso Sea, are lost in the immensity of the oceans.

Green metaphytes[114] predominate on land; in this group, the grasses multiply at the greatest speed and possess the greatest geochemical energy, whereas trees appear to have a lower velocity. In the ocean, green protista have the highest velocity.

The speed of transmission v, for metaphytes, probably does not exceed a few centimeters per second. Green protista have a speed of thousands of centimeters per second, besting the metaphytes by hundreds of times with regard to power of multiplication, and clearly demonstrating the difference between marine and terrestrial life. Although green life is perhaps less dominant in the sea than on the soil, the total mass of green life in the ocean exceeds that on land because of the larger size of the ocean itself. The green protista of the ocean are the major agents in the transformation of luminous solar energy into chemical energy on our planet.[115]

48 The energetic character of green vegetation can be expressed quantitatively in a way that shows the distinction between green life on land and in the sea. The formula $Nn = 2^{n\Delta}$ gives the growth (α) of an organism in 24 hours due to multiplication. If we start with a single organism (n = 1 on the first day), we shall have:

$$2^{\Delta} - 1 = \alpha$$

$$2^{\Delta} = \alpha + 1 \text{ and } 2^{n\Delta} = (\alpha + 1)^n$$

The quantity a is a constant for each species; it is the number of individuals that will grow in 24 hours starting from a single organism. The magnitude $(\alpha + 1)^n$ is the number of individuals created by multiplication on the nth day: $(\alpha + 1)^n = Nn$.

The following example shows the significance of these numbers. The average multiplication of plankton, according to Lohmann, can be expressed by the constant $(\alpha + 1) = 1.2996$, taking into account the destruction and assimilation of the

113 That is, those with visible reproductive organs such as flowers and cones.

114 Land plants, members of kingdom Plantae.

115 Vernadsky's assertions here have not been borne out. The mass of photoautotrophs on land (738×10^{15} grams of organic carbon) vastly outweighs the mass of photoautotrophs in the sea (1.7×10^{15} grams of organic carbon) (Romankevich, 1988). This discrepancy has recently been attributed to upward nutrient transport by vascular plants on land (McMenamin and McMenamin, 1994).

plankton by other organisms. The same constant for an average crop of wheat in France is 1.0130. These numbers correspond to the ideal average values for wheat or plankton after 24 hours of multiplication. So the ratio of the number of plankton individuals to those of wheat is

$$\frac{1.2996}{1.0130} = 1.2829 = \delta$$

This ratio is multiplied every 24 hours by δ, being δ^n after n days.

On the 20th day, the value would be 145.8; on the hundredth, the number of plankton would exceed that of wheat plants by a factor of 6.28 × 10. After a year, neglecting the fact that the multiplication of wheat is arrested for several months, the ratio of the populations (δ^{365}) attains the astronomical figure of 3.1×10^{39}. The initial difference between the full-grown herbaceous plant (weighing tens of grams) and the microscopic plankton (weighing 10^{-10} to 10^{-6} grams) is dwarfed by the difference in intensity of multiplication.

The green world of the ocean gives a similar result, due to the speed of circulation of its matter.[116] The force of solar radiation allows it to create a mass equivalent in weight to the Earth's crust (§44) in 70 days or less. Herbaceous vegetation on land would require years to produce this quantity of matter—in the case of *Solanum nigrum*, for example, five years.

These figures, of course, do not give a correct perspective of the relative roles of herbaceous vegetation and green plankton in the biosphere, because in this method of comparison the difference grows enormously with time. In the five-year span mentioned above for *Solanum nigrum*, for example, the amount of green plankton that could be produced would be hard to express in conceivable figures.

49 It is not accidental that living green matter on land differs from that in the sea, because the action of solar radiation in a transparent, liquid medium is not the same as on solid, opaque Earth. The world of plankton controls geochemical effects in the oceans, and also on land wherever aqueous life exists.

The difference in energy possessed by these two kinds of living matter is represented by the quantity δ^n, and also by the mass (m) of the individuals created. This mass is determined by the product of the number of individuals created, and their average weight (P): $m = P(1 + \alpha)^n$. Small organisms would have the advantage over large ones, energetically-speaking, only if they really could produce a larger mass in the biosphere.

116 The point, then, of the immediately preceding mathematical calculations is that differences in the intensity of multiplication between complex, larger organisms and smaller ones (differences which grow astronomically large with passage of time) are a direct result of the differing relative respiratory surfaces of large and small organisms, respectively. Smaller organisms have a much greater surface to volume ratio (and hence greater respiratory surface area to volume ratio) in comparison to larger, more complex organisms. This accounts for, all other things being equal, the disparity between large and small organisms in their velocity or speed of transmission (V), and then of course the much greater disparity (because it is calculated using the square of V) between their respective geochemical energies ($PV^2/2$). In comparisons of this sort, the microbes outperform more complex organisms by an overwhelming margin, assuming they are able to create sufficient biomass. Vernadsky thus provides the quantification required for comparisons of geochemical energy between species.

Any system reaches a stable equilibrium when its free energy is reduced to a minimum under the given conditions; that is, when all work possible in these conditions is being produced. All processes, of both the biosphere and the crust, are determined by conditions of equilibrium in the mechanical system of which they are a part.[117]

Solar radiation and the living green matter of the biosphere, taken together, constitute a system of this kind. When solar radiation has produced the maximum work, and created the greatest possible mass of green organisms, this system has reached a stable equilibrium.

Since solar radiation cannot penetrate deeply into solid earth, the layer of green matter it creates there is limited in thickness.

The environment gives all the advantages to large plants, grasses and trees as compared to green protista. The former create a larger quantity of living matter, although they take a longer time to do it. Unicellular organisms can produce only a very thin layer of living matter on the land surface, and soon reach a stationary state (§37) at the limits of their development. In the system of solar radiation and solid earth taken as a whole, unicellular organisms are an unstable form,[118] because herbaceous and wooded vegetation, in spite of their smaller reserve of geochemical energy, can produce much more work, and a greater quantity of living matter.

50 The effects of this are seen everywhere. In early spring, when life awakens, the steppe becomes covered in a few days by a thin layer of unicellular algae (chiefly larger cyanobacteria and algae such as *Nostoc*). This green coating develops rapidly, but soon disappears, making room for the slower-growing herbaceous plants. Due to the properties of the opaque earth, the grass takes the upper hand, although the *Nostoc* has more geochemical energy. Everywhere, tree bark, stones, and soil are rapidly covered by fast-developing *Protococcus*. In damp weather, these change in only a few hours from cells weighing millionths of a milligram into living masses weighing decigrams or grams. But even in the most favorable conditions, their development soon stops. As in Holland's sycamore groves, tree trunks are covered by a continuous layer of *Protococcus* in stable equilibrium, further development of which is arrested by the opacity of the matter on which they live. The fate of their aqueous cousins, freely developing in a transparent medium hundreds of meters deep, is quite different.

117 Vernadsky offers here a plausible explanation for the stability of Earth's climate; it represents a minimum energy configuration. See McMenamin, 1997b.

118 Vernadsky is saying here that unicellular organisms reach a stable state only in the absence of competing large plants, as might have been the case during the Precambrian. Large plants today prevent the microbes from reaching this stable or stationary state.

Trees and grasses, growing in a new transparent medium (the troposphere), have developed forms according to the principles of energetics and mechanics. Unicellular organisms may not follow them on this path. Even the appearance of trees and grasses, the infinite variety of their forms, displays the tendency to produce maximum work and to attain maximum bulk of living matter.

To reach this aim, they created a new medium for life—the atmosphere.[119]

51 In the ocean, where solar radiation penetrates to a depth of hundreds of meters, unicellular algae, with higher geochemical energy, can create living matter at an incomparably faster rate than can the plants and trees of land. In the ocean, solar radiation is utilized to its utmost. The lowest grade of photosynthetic organism has a stable vital form: this leads to an exceptional abundance of animal life, which rapidly assimilates the phytoplankton, enabling the latter to transform an even greater quantity of solar energy into living mass.

52 Thus, solar radiation as the carrier of cosmic energy not only initiates its own transformation into terrestrial chemical energy, but also actually creates the transformers themselves. Taken together, these make up living nature, which assumes different aspects on land and in the water.

The establishment of the life forms is thus in accordance with the way solar (cosmic) energy changes the structure of living nature, by controlling the ratio of autotrophic to heterotrophic organisms. A precise understanding of the laws of equilibrium that govern this is only now beginning to appear.

Cosmic energy determines the pressure of life (§27), which can be regarded as the transmission of solar energy to the Earth's surface.[120] This pressure arises from multiplication, and continually makes itself felt in civilized life. When man removes green vegetation from a region of the Earth, he changes the appearance of virgin nature, and must resist the pressure of life, expending energy and performing work equivalent to this pressure. If he stops this defense against green vegetation, his works are swallowed up at once by a mass of organisms that will repossess, whenever and wherever possible, any surface man has taken from them.

This pressure is apparent in the *ubiquity of life*. There are no regions which have always been devoid of life. We encounter vestiges of life on[121] the most arid rocks, in fields of snow and ice, in stony and sandy areas. Photosynthetic organisms are carried to such places mechanically; microscopic life is constantly born, only to disappear again; animals pass by, and some remain to live there. Some richly-animated concentrations of life are observed, but not as a green world of transformers. Birds, beasts, insects, spiders, bacteria, and sometimes green protista make up the populations of these apparently inanimate regions, which are really *azoic* only in comparison with the "immobile" green world of plants. These regions can be likened to those of our latitudes where green life disappears, temporarily, beneath a clothing of snow, during the winter suspension of photosynthesis.

Phenomena of this sort have existed on our planet throughout geological history, but always to a relatively limited extent. Life has always tended to become master of apparently lifeless regions, adapting itself to ambient conditions. Every empty space in living nature, no matter how constituted, must be filled in the course of time. Thus, new species and subspecies of flora and fauna will populate azoic areas, newly formed land areas, and aquatic basins. It is curious and important to note that the structures of these new organisms, as well as the structures of their ancestors, contain certain preformed properties that are required for the specific conditions of the new environment.[122] This morphological preformation and the ubiquity of life are both manifestations of the energetic principles of the pressure of life.

Azoic surfaces, or surfaces poor in life, are limited in extent at any given moment of the planet's existence. But they always exist, and are more evident on land than in the hydrosphere. We do not know the reason for the restrictions they impose on vital geochemical energy; nor do we know whether there exists a definite and inviolable relationship between the forces on the Earth that are opposed to life, on one hand, and the life-enhancing and not yet fully understood force of solar radiation on the other.

53 The ways in which green vegetation has adapted so as to attract cosmic energy can be seen in many ways. Photosynthesis takes place principally in tiny plastids, which are smaller than the cells they occupy. Myriads of these are dispersed in plants, to which they impart the green color.

Examination of any green organism will show how it is both generally and specifically adapted to attract *all* the luminous

119 As Vernadsky later notes, Dumas and Boussingault in 1844 considered life to be an "appendage of the atmosphere." More recently it has been argued that the atmosphere is a nonliving product of life, like a spider's web, a view Vernadsky seems to have anticipated here.

120 This is a remarkable passage. Thus life not only plays the role of horizontal transmission of matter, but also horizontal transmission of vertically-incoming solar energy.

121 Or in the rocks, as in the case of cryptoendolithic Antarctic lichens.

122 Here Vernadsky alludes to what is today called preadaptation or exaptation. Evolutionists now feel that organisms have no ability to anticipate environmental change. But once such change has occurred (or sometimes without any such change), organs useful for one function can switch their function and provide the organism bearing them with a new adaptation—hence the appearance that they were "preadapted." See Cuénot, 1894a, 1894b and 1925.

radiation accessible to it. Leaf size and distribution in plants is so organized that not a single ray of light escapes the microscopic apparatus which transforms the captured energy. Radiation reaching Earth is gathered by organisms lying in wait. Each photosynthetic organism is part of a mobile mechanism more perfect than any created by our will and intelligence.

The structure of vegetation attests to this. The surface of leaves in forests and prairies is tens of times larger than the area of the ground they cover. The leaves in meadows in our latitudes are 22 to 38 times larger in area; those of a field of white lucerne are 85.5 times larger; of a beech forest, 7.5 times; and so on, even without considering the organic world that fills empty spaces rapidly with large-sized plants. In Russian forests, the trees are reinforced by herbaceous vegetation in the soil, by mosses and lichens which climb their trunks, and by green algae which cover them even under unfavorable conditions.[123] Only by great effort and energy can man achieve any degree of homogeneity in the cultivated areas of the Earth, where green weeds are constantly shooting up.

This structure was strikingly demonstrated in virgin nature before the appearance of man, and we can still study its traces. In the uncultivated regions of "virgin steppe" which survive in central Russia, one can observe a natural equilibrium that has existed for centuries, and could be reestablished everywhere if man did not oppose it. J. Paczoski[124] has described the steppe of "Kovyl" or needle grass (*Stipa capillata*) of Kherson: "It gave the impression of a sea; one could see no vegetation except the needle grass[125] which rose as high as a man's waist and higher. The mass of this vegetation covered the land almost continuously, protecting it by shade and helping it to conserve the humidity of the soil, so that lichens and mosses were able to grow between the tufts of the leaves and remain green at the height of summer."[126]

Earlier naturalists have similarly described the virgin savannas of Central America. F. d'Azara (1781-1801) writes[127] that the plants were "so thick that the earth could only be seen on the roads, in streams, or in gulleys."

These virgin steppes and savannas are exceptional areas that have escaped the hand of civilized man, whose green fields have largely replaced them.

In our latitudes, vegetation lives with a periodicity controlled by an astronomical phenomenon—the rotation of the Earth around the sun.

123 The wording at the end of this sentence suggests, as inferred earlier, exposure to the ideas of the symbiogeneticists and to the ideas that organisms of different species can aid one another.

124 See Paczoski, 1908.

125 Needle grass, or *Stipa capillata*, is referred to in Russian as *tyrsa*. It is a tough grass with sharp leaves. Most species of the genus *Stipa* are perennials, and they are a characteristic plant of the steppes throughout the world.

126 This same observation strongly influenced Kropotkin.

127 See d'Azara, 1905.

54 The same picture of saturation of the Earth's surface by green matter can be observed in all other phenomena of plant life: forest stands of tropical and subtropical regions, the taiga of septentrional and temperate latitudes, savannas and tundras. These are the coating with which green matter permanently or periodically covers our planet, if the hand of man has not been present. Man, alone, violates the established order; and it is a question whether he diminishes geochemical energy, or simply distributes the green transformers in a different way.[128]

Grouped vegetation and isolated plants of many forms are so arranged as to capture solar radiation, and to prevent its escaping the green-chlorophyll plastids.

Generally radiation cannot reach any locality of the Earth's surface[129] without passing through a layer of living matter that has multiplied by *over one hundred times* the surface area that would otherwise be present if life were absent from the site.

55 Land comprises 29.2 percent of the surface of the globe; all the rest is occupied by the sea, where the principal mass of green living matter exists and most of the luminous solar energy is transformed into active chemical energy.

The green color of living matter in the sea is not usually noticed, since it is dispersed in myriad microscopic, unicellular algae. They swim freely, sometimes in crowds, and at other times spread out over millions of square miles of ocean. They can be found wherever solar radiation penetrates, up to 400 meters water depth, but mostly between 20 and 50 meters from the surface, rising and sinking in perpetual movement. Their multiplication varies according to temperature and other conditions, including the rotation of the planet around the sun.

Incident sunlight is undoubtedly utilized in full by these organisms. Green algae, cyanobacteria, brown algae, and red algae succeed each other in depth in a regular order.[130] The red phycochromaceae use the blue rays, the final traces of solar light not absorbed by water. As W. Engelmann has shown,[131] all these algae, each type with its own particular color, are adapted to produce maximum photosynthesis in the luminous conditions peculiar to their aqueous medium.[132]

This succession of organisms with increasing depth is a ubiquitous feature of the hydrosphere. In shallows, or in special structures linked with geological history such as the Sargasso Sea, the plankton, though invisible to the naked eye, are intensified by immense, floating fields or forests of algae and plants,

128 Vernadsky never makes up his mind about the true role of humans in the biosphere (Vernadsky, 1945).

129 Here Vernadsky means any forested locality of Earth's surface.

130 The farbstreifensandwatt, or "color-striped sand," is a within-sediment bacterial and algal community showing this same type of stratified succession. The microbial photosynthesizers of the farstreifensandwatt partition the light by wavelength and intensity as it passes through the sand layer. See Schulz, 1937; Hoffmann, 1949; and Krumbien, Paterson and Stal, 1994.

131 See Engelmann 1984; and 1861.

132 They also have distinctive characteristics of metal accumulation (Tropin and Zolotukhina, 1994).

some of them very large. These are chemical laboratories, with energy more powerful than the most massive forests of solid earth. The total surface they occupy, however, is relatively small — only a few percent of the surface area occupied by the plankton.

56 Thus, we see that the hydrosphere, a majority of the planetary surface, is always suffused with an unbroken layer of green energy transformers, as is most of the continental area in the appropriate seasons. Places poor in life, such as glaciers, and azoic regions constitute only 5 to 6 percent of the total surface area; with this taken into account, the layer of green matter still has a surface area far greater than that of the Earth and, by virtue of its influence, belongs to an order of phenomena on a cosmic-planetary scale.

If one adds the surface area of the vegetation on land to that of phytoplankton in oceanic water column, the resulting sum represents a surface area vaster than the ocean itself. In fact, the photosynthesizers of Earth can be shown to have approximately the same surface area as Jupiter — 6.3 × 10 square kilometers.*

It is no coincidence that the surface area of the biosphere, an entity of cosmic scale, rivals that of the other major objects in the solar system.

The Earth's surface area is a little less than 0.01 percent (0.0086%) of that of the sun, whereas the photosynthesizing surface area of the biosphere is of an altogether different order: 0.86 to 4.2 percent of the sun's surface.[133]

57 These figures, obviously, correspond approximately to the fraction of solar energy collected by living green matter in the biosphere. This coincidence might serve as a departure point from which we can begin to explain the verdure of the Earth.

The solar energy absorbed by organisms is only a small part of what falls on the Earth's surface, and the latter is an insignificant fraction of the sun's total radiation. According to S. Arrhenius,[134] the Earth receives from the sun 1.66×10^{21} kilocalories per year, while the sun emits 4×10^{30}.

This is the only cosmic energy we can consider in our present state of knowledge. The total radiation that reaches the Earth from all stars is probably less than 3.1×10^{-5} percent of that from the sun, as I. Newton demonstrated.[135] The energy from the planets and the moon, mostly reflected solar radiation, is less than one ten-thousandth of the total from the sun.

* This assumes that 5 percent of Earth's
surface is devoid of green vegetation, and that the green, absorbing surface is increased by a factor of 100 to 500 by
multiplication. The maximum green area then corresponds to 5.1×10^{10} to 2.55×10^{11} square kilometers.

133 Vernadsky's figure here is unrealistically high; the surface area of Earth's vegetation is approximately equal to the planetary surface area (Schlesinger, 1991).

134 See Arrhenius, 1896.

135 See Newton, 1989 .

A considerable part of all the incoming energy is absorbed by the atmosphere and only 40 percent (6.7×10^{20} calories per year) actually reaches the surface. This is available for green vegetation, but most of it goes into thermal processes in the crust, the ocean, and the atmosphere. Living matter also absorbs a considerable amount in the form of heat which, while playing an immense role in the sustenance of life, does not directly participate in the creation of the new chemical compounds that represent the chemical work of life.

For chemical work, i.e., the creation of organic compounds that are unstable in the thermodynamic field of the biosphere (§89), green vegetation uses primarily wavelengths between 670 and 735 nanometers (Dangeard and Desroche, 1910-1911[136]). Other portions of the visible part of the electromagnetic spectrum, at wavelengths between 300 and 770 nanometers, are also utilized by green plants to power photosynthesis, but are not used as intensely as those within the 670-735 range. The fact that green plants make use of only a small part of the solar radiation that falls on them is related to the requirements of the chemical work required, rather than to imperfections in the transforming apparatus.

According to J. Boussingault,[137] one percent of the solar energy received by a cultivated green field may be used for conversion of energy into organic, combustible[138] matter. S. Arrhenius[139] calculates that this figure may reach two percent in areas of intense cultivation. H. T. Brown and F. Escombe[140] found by direct observation that it reaches 0.72 percent for green leaves. Forest-covered surfaces make use of barely 0.33 percent, according to calculations based upon woody tissue.

58 These are undoubtedly minimum figures. In Boussingault's calculation,[141] which included Arrhenius' correction,[142] only vegetation on land was considered. It should be assumed, moreover, that the fertility of the soil is increased by cultivation, and that the favorable conditions we create apply not only for valuable cultivated plants, but also for weeds. These calculations do not account for the lives of the weeds and the microscopic photosynthesizers that benefit from the favorable conditions provided by cultivation and manure. The Earth also has rich concentrations of life other than fields, such as marshes, humid forests, and prairies, where the quantity of life is higher than in human plantings. (§150 et seq.)

The principal mass of green vegetation is in the oceans,[143] where the animal world assimilates vegetable matter as fast as

136 See Dangeard, 1910a, b, 1911a-d; and Desroche, 1911a-e.

137 See Boussingault, 1860-84.

138 It is likely that Vernadsky used the terms "organic" and "combustible" as synonyms.

139 See Arrhenius, 1896.

140 See Brown and Escombe, 1898, 1900.

141 See Boussingault, 1860-84.

142 See Arrhenius, 1896.

143 As noted earlier, this statement is incorrect.

the latter is produced. The rate of production depends upon the quantity of green life per unit area, and appears to be about the same as on land. The collections of heterotrophic animal life, which are thus formed in the plankton and benthos of the ocean, occur on a scale that can rarely, if ever, be seen on land.

We have mentioned that the minimum figure of Arrhenius[144] must be increased, and it should be noted that a correction of the order indicated by this author is already apparent.

Green matter absorbs and utilizes, it would appear, up to 2 percent or more of radiant solar energy. This figure falls within the limits 0.8 to 4.2 percent, which we calculated as the fraction of the solar surface which would have an area equal to the green transforming surface of the biosphere (§56). Since green plants have at their disposal only 40 percent of the total solar energy reaching the planet, the 2 percent that they use corresponds to 0.8 percent of the total solar energy.

59 This coincidence can be explained only by admitting the existence of an apparatus, in the mechanism of the biosphere, that completely utilizes a definite part of the solar spectrum. The terrestrial transforming surface created by the energy of radiation will correspond to the fraction of total solar energy that lies in the spectral regions capable of producing chemical work on Earth.

We can represent the radiating surface of the rotating sun that lights our planet by a luminous, flat surface of length AB (Fig. 1). Luminous vibrations are constantly directed to the Earth from each point of this surface. Only a few hundredths of *m* percent of these waves, having proper wavelengths, can be converted by green living matter into active chemical energy in the biosphere.

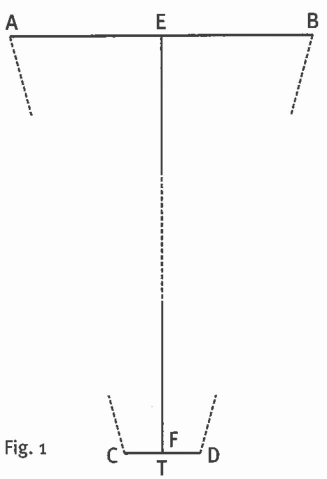

Fig. 1

The rotating surface of the Earth can also be represented, by a plane surface illuminated by solar rays. Considering the enormous size of the solar diameter, and the distance from the Earth to the sun, this surface can be expressed in the figure by the point T, which may be considered as the focus of the solar rays leaving the luminous surface AB.

The green transmuting apparatus in the biosphere is composed of a very fine layer of organized particles, the chloroplasts. Their action is proportional to their surface, because the chlorophyll itself is quite opaque to the chemically-active frequencies of light it transforms. The maximum transformation of solar energy by green plants will occur when there is a receiver on the Earth having a plane surface at least equal to *m* percent of the luminous (plane) surface of the sun. In this case, all the rays necessary for the Earth will be absorbed by the chlorophyll-bearing apparatus.

144 See Arrhenius, 1896.

In the illustration, CD represents the diameter of a circle with surface equal to 2 percent of the solar surface;* AB represents the diameter of a circle with surface equal to the whole radiating area of the sun; CD similarly represents the area receptive to radiations falling on the Earth; T corresponds to the surface of the Earth. Unknown relationships probably exist connecting the solar radiation, its character (the fraction *m* of chemically-active radiations in the biosphere), and the plane surface of green vegetation and of azoic areas. It follows that the cosmic character of the biosphere should have a profound influence on the biota thus formed.

60 Living matter always retains some of the radiant energy it receives, in an amount corresponding to the quantity of organisms. All empirical facts indicate that the quantity of life on the Earth's surface remains unchanged not only during short periods, but that it has undergone practically no modification† throughout geological periods from the Archean to our own times.

The fact that living matter is formed by radiant energy lends great importance to the empirical generalization regarding the constancy of the mass of living matter in the biosphere, since it forms a connection with an astronomical phenomenon; namely, the intensity of solar radiation. No deviations of any importance in this intensity throughout geological time can be verified. When one considers the connection between green living matter—the principal element of life—and solar radiations of certain wavelengths, as well as our perception that the mechanism of the biosphere is adapted to complete utilization of such rays by green vegetation, we find a fresh and independent indication of the constancy of the quantity of living matter in the biosphere.

61 The quantity of energy captured every moment in the form of living matter can be calculated. According to S. Arrhenius,[145]

* In the illustration, surfaces are reduced to areas, taking the radius of a circle having an area equal to that of the sun as unity.
The radius of the circle having the same area as the sun:
$r = 4.3952 \times 10^6$ kilometers (taken as 1)

The radius of the circle having the same area as the Earth:
$r_1 = 1.2741 \times 10^4$ kilometers (taken as 0.00918)

The radius of the circle having the same area as 0.02 × area of the sun:
$r_2 = 1.9650 \times 10^5$ kilometers (taken as 0.14148)

The radius of the circle having the same area as 0.008 x area of the sun:
$r_3 = 1.2425 \times 10^5$ kilometers (taken as 0.08947)

The mean distance from Earth to sun is 1.4950×10^8 km (taken as 215, relative to the radius of a circle having area equal to that of the sun).

† That is, it oscillates about the stable static state, as in the case of all equilibria.

145 See Arrhenius, 1896.

the combustible, organic compounds produced by green vegetation contain 0.024 percent of the total solar energy reaching the biosphere – 1.6×10^{17} kilocalories, in a one-year period.

Even on a planetary scale, this is a high figure, but it seems to me that it should be even larger than stated. We have tried to show elsewhere* that the mass of organic matter calculated by S. Arrhenius,[146] based upon the annual work of the sun, should be increased ten times, and perhaps more. It is probable that more than 0.25 percent of the solar energy collected annually by the biosphere is constantly stored in living matter, in compounds that exist in a special thermodynamic field,[147] different from the field of inert matter in the biosphere.

The quantity of substances constantly moving through life is huge, as illustrated by the production of free oxygen (approximately 1.5×10^{21} grams/year).[148] Even larger, however, is the effect of the creatures that are constantly dying, and being replaced by multiplication. We have seen (§45) that the mass of elements that migrate in the course of a year exceeds, by many times, the weight of the upper 16 kilometers of the Earth's crust (of the order of 10^{25} grams).

As far as can be judged, the energy input to the biosphere, in the course of a year, by living matter does not much exceed the energy that living matter has retained in its thermodynamic field for hundreds of millions of years. This includes at least 1×10^{18} kilocalories in the form of combustible compounds. At least 2 percent of the energy falling on the surface of the earth and oceans is expended in the work of new creation and reconstruction; i.e., at least 1.5×10^{19} kilocalories. Even if later study should increase this figure, its order of magnitude can hardly be different from 10^{19}.

Regarding the quantity of living matter as constant throughout geological time, the energy contained in its combustible part can be regarded as an inherent and constant part of life. A few times 10^{19} kilocalories will thus be the energy transmitted by life, annually, in the biosphere.

* See Vernadsky, 1924, p. 308.

146 See Arrhenius, 1896.

147 Such as the cambial wood of trees.

148 Vernadsky had a math (or proofreading) problem with his oxygen values. He uses this same number earlier (1.5×10^{21}) to describe the total resevoir of atmospheric oxygen, whereas here he is using it to describe annual generation. The correct value is closer to 2.7×10^{17} grams of O_2/year.

Some Remarks on Living Matter in the Mechanism of the Biosphere

62 Photosynthetic living matter does not include all the essential manifestations of life in the biosphere, because the chemistry of the biosphere is only partially controlled by the vegetable world. Certain regularities that can be regarded as empirical (if not fully understood) generalizations are frequently encountered in nature, and in spite of their uncertainties must be taken into account. The most essential of them are described below.

The eminent naturalist K. E. Baer long ago noted a peculiarity that governs the whole geochemical history of living matter – *the law of economy of utilization* of simple chemical bodies after they have entered into the biosphere. Baer demonstrated this in connection with carbon, and later with nitrogen; it can be extended to the geochemical history of all chemical elements.[149]

Economy in the utilization of chemical elements by living matter is manifested, in the first instance, within organisms themselves. When an element enters an organism, it passes through a long series of states, forming parts of many compounds, before it becomes lost to the organism. In addition, the organism introduces into its system only the required quantities of these elements, avoiding any excesses. It makes choices, seizing some and leaving others, always in a definite proportion.[150] This aspect of the phenomenon to which Baer gave his attention is evidently connected with the autonomy of the organism, and with the systems of equilibrium[151] which enable it to achieve stability and to minimize its free energy.

In larger masses of living matter, this law of economy is demonstrated with even greater clarity. Once atoms become involved in the vital vortices of living matter, they escape only with difficulty into the inert matter of the biosphere, and some perhaps never escape at all. Countless heterogeneous mechanisms absorb atoms into their moving medium, and preserve them by carrying them from one vital vortex to another. These include parasites, organisms which assimilate other organisms, new generations produced by multiplication, symbioses, and saprophytes.[152] The latter make use of the remains of life, much of which are still living because they are impregnated with microscopic forms, transforming them rapidly into a form of living matter.

So it has been, throughout the whole vital cycle, for hundreds

149 See Baer, 1828, 1876.

150 And with a selectivity that can distiguish heavier from lighter isotopes of such elements as oxygen and carbon.

151 American biologists today call this equilibrium *homeostasis*, but there was no such term in Vernadsky's time.

152 One could perhaps carry this thought further and argue that, over geological time, the ratio of "living matter" to "inert matter" in the biosphere has increased, with the forces of life tending to increase the amount of matter in circulation as part of something that is alive. Parasites and hyperparasites have colonized the land-based living environment of their hosts' tissues, environments that (partly as a result of these symbioses) have spread over the surface of Earth.

153 Presumably Vernadsky is referring here back to what he had earlier called "compounds that exist in a special thermodynamic field," such as wood and certain types of animal tissues.

154 Indeed, isotopic fractionation, now a well-known characteristic of life, was first hypothesized in Russia by Vernadksy (1939b). Vernadsky carried his view of life as a geological force to the point of proposing that biogeochemistry of elements in organisms be used as a form of taxonomy of organisms! In the paper cited above (p. 7-8), Vernadsky seems to express some disappointment that the technique is not working out as cleanly and simply as he had hoped:

"Proceeding from this general statement, it has been possible to show by the work of our Laboratory that [emphasis his] the *atomic composition of organisms, plants, and animals is as characteristic a feature as their morphological form or physiological structure* or as their appearance and internal structure. It should be noted that the elementary chemical composition of living organism[s] of the same species taken at different times, in different years, at different places, for instance in Kiev or in Leningrad, varies less than a natural isomorphous mixture of minerals, of millions of years. A portion of the atoms of the unchangeable covering layer, which possesses a nearly uniform level of energy of about 10^{19} kilocalories, never leaves this vital cycle. As visualized by Baer, life is parsimonious in its expenditure of absorbed matter, and parts from it only with difficulty. Life does not easily relinquish the matter of life, and these atoms remain associated with life for long stretches of time.

63 Because of the law of economy, there can be atoms that have lived in the framework of living matter throughout whole geological periods, moving and migrating, but never returning to the source of inert matter.[153]

The unexpected picture outlined by this empirical generalization forces us to examine its consequences and seek an explanation. We can proceed only hypothetically. To begin with, this generalization raises a question that science has not yet considered, although it has been discussed in philosophical and theological circles: are the atoms which have been absorbed in this way, by living matter, the same as those of inert matter? Or do special isotopic mixtures exist among them?[154] Only experiment can give an answer to this problem, which is of great interest for contemporary science.

64 The exchange of gases between organisms and their surrounding medium is a life process of immense importance in the biosphere (§42). One part of this exchange has been explained by L. Lavoisier[155] as combustion, by means of which atoms of carbon, hydrogen, and oxygen perpetually go and come, inside and outside living vortices.

Combustion probably does not reach the essential substratum of life, the protoplasm. It is possible that the atoms of carbon set free as carbon dioxide by the living organism are derived from matter foreign to the organism, such as food, and not from elements that are part of its framework. If this is so, then the atoms that are absorbed and retained by living matter will collect together only in protoplasm and its structures.[156]

The theory of the atomic stability of protoplasm originated with C. Bernard.[157] Although not accepted by orthodox biologists, it resurfaces from time to time and awakens the interest of scholars. Perhaps a connection exists between Bernard's ideas, Baer's generalization on vital economy,[158] and the empirical fact of the constancy of the quantity of life in the biosphere. All these ideas may be connected with *the invariability of the quantity of*

easily expressed by stoichiometric formulas. The composition of different species of duckweed or insects is more constant than the composition of orthoclases [feldspars] or epidotes [greenish calcsilicate minerals] from different localities. For organisms there is a narrow range within which the composition varies, but there are no stoichiometric[ally] simple ratios for them . . . It may be assumed that in all the cases so far investigated we find a confirmation of the fundamental principle of biogeochemistry, namely, that *numerical biogeochemical features are specific, racial and generic characteristics of the living organisms.* As yet it has been possible to establish it precisely for many species of plants and insects. But it is already clear that this is a general phenomenon. The relations are not so simple as one could have presumed. Many questions evidently arise that require biological criticism."

It is clear from this passage that Vernadsky not only wishes to view life as a geological force, but also individual life forms as minerals. This view continues to influence Russian work on the interpretation of metal contents of various organisms (e. g., Tropin and Zolotukhina, 1994; and Timonin, 1993) and on the ability of microorganisms to mobilize metals and influence the history of mineralogy (Karavaiko, Kuznetsov and Golomzik, 1972; and Kuznetsov, Ivanov and Lyalikova, 1962). Vernadsky's research on the history of minerals of Earth's crust (1959) has generated a unique development of Russian thought on this issue (e. g., A. S. Povarennykh, 1970). Vernadsky's imprint is also apparent in the development of Russian thought on the relationship between the biosphere, granites and ore deposits (see Tauson, 1977).

At least one western scientist has focused on elemental distinctions between taxa (Morowitz, 1968). Morowitz's Table 3-2 recalls Vernadsky's geochemical taxonomy of organisms, and compares the C, H, N, O, P, S, Ca, Na, K, Mg, Cl, Fe, Si, Zn, Rb, Cu, Br, Sn, Mn, I, Al, and Pb contents of man, alfalfa, copepod, and bacteria. Data for the copepod (*Calanus finmarchicus*) were taken from Vernadsky paper, 1933a, p. 91.

155 See Lavoisier, 1892.

protoplasmic formations in the biosphere throughout geological time.

65 The study of life-phenomena on the scale of the biosphere shows that the functions fulfilled by living matter, in its ordered and complex mechanism, are profoundly reflected in the properties and structures of living things.

In this connection, the exchange of gases must be placed in the first rank. There is a close link between breathing and the gaseous exchange of the planet.

J. B. Dumas and J. Boussingault showed,[159] at a remarkable conference in Paris in 1844, that living matter can be taken as an *appendage of the atmosphere.*[160] Living matter builds bodies of organisms out of atmospheric gases such as oxygen, carbon dioxide, and water, together with compounds of nitrogen and sulfur, converting these gases into liquid and solid combustibles that collect the cosmic energy of the sun. After death, it restores these same gaseous elements to the atmosphere by means of life's processes.

This idea accords well with the facts. The firm, generative connection between life and the gases of the biosphere is more profound than it seems at first sight. The gases of the biosphere are generatively linked with living matter which, in turn, determines the essential chemical composition of the atmosphere. We dealt earlier with this phenomenon, in speaking of gaseous exchange in relation to the creation and control of multiplication and the geochemical energy of organisms. (§42)

The gases of the entire atmosphere are in an equilibrium state of dynamic and perpetual exchange with living matter. Gases freed by living matter promptly return to it. They enter into and depart from organisms almost instantaneously. The gaseous current of the biosphere is thus closely connected with photosynthesis, the cosmic energy factor.

66 After destruction of an organism, most of its atoms return immediately to living matter, but a small amount leave the vital process for a long time. This is not accidental. The small percentage is probably constant and unchangeable for each element, and returns to living matter by another path, thousands or millions of years afterwards. During this interval, the compounds set free by living matter play an important role in the history of the biosphere, and even of the entire crust, because a significant fraction of their atoms *leave the biosphere* for extended periods.

156 It is now known, of course, that organisms are able to catabolize both food taken in and biomolecules forming part of the body structure. Vernadsky appears to be arguing here for a permanent sequestering of some atoms in living structure, but this is not generally the case.

157 See Bernard, 1866, 1878.

158 See von Baer, 1876.

159 See Boussingault and Dumas, 1844a abd 1844b. But also see Boussingault and Dumas, 1841, which may be the report to which Vernadsky is referring; in that case Vernadsky is incorrect about the date of the conference.

160 Dumas and Boussingault thus anticipated the Lovelockian view of the intimate relationship between life and atmosphere, matching Lamarck's anticipation of Vernadsky's articulation of full concept of the biosphere.

We now have a new process to consider: *the slow penetration into the Earth of radiant energy from the sun.*[161] By this process, living matter transforms the biosphere and the crust. It constantly secretes part of the elements that pass through it, creating an enormous mass of minerals unique to life; it also penetrates inert matter of the biosphere with the fine powder of its own debris.[162] Living matter uses its cosmic energy to produce modifications in abiogenic compounds (§140 et seq.). Radiant energy, penetrating ever-more-deeply due to the action of living matter on the interior of the planet, has altered the Earth's crust throughout the whole depth accessible to observation. Biogenic minerals converted into phreatic[163] molecular systems have been the instruments of this penetration.

The inert matter of the biosphere is largely the creation of life.[164]

We return, in a new venue, to the ideas of natural philosophers of the early 19th century: L. Ocken,[165] H. Steffens,[166] and J. Lamarck.[167] Obsessed with the primordial importance of life in geological phenomena, these thinkers grasped the history of the Earth's crust more profoundly, and in better accordance with empirical facts, than generations of the strictly observation driven geologists who followed.[168]

It is curious that these effects of life on the matter of the biosphere, particularly on the creation of agglomerations of vadose minerals, are chiefly connected with the activity of aqueous organisms. The constant displacement of aqueous basins, in geological times, spread chemical free energy of cosmic origin throughout the planet. These phenomena appear as a stable dynamic equilibrium, and the masses of matter that play a part in them are as unchanging as the controlling energy of the sun.

67 In short, a considerable amount of matter in the biosphere has been accumulated and united by living organisms, and transformed by the energy of the sun. The weight of the biosphere should amount to some 10^{24} grams.[169] Of this, activated living matter that absorbs cosmic energy accounts for, at most, one percent, and probably only a fraction of one percent. In some places, however, this activated living matter predominates, constituting 25 percent of thin beds such as soil.

The appearance and formation of living matter on our planet is clearly a phenomenon of cosmic character. It is also very clear that living matter becomes manifest without abiogenesis. In other words, living organisms have always sprung from living organisms during the whole of geological history;[170] they are all genetically connected; and nowhere can solar radiation be converted into chemical energy independent of a prior, living organism.

We do not know how the extraordinary mechanism of the Earth's crust could have been formed. This mechanism is, and always has been, saturated with life. Although we do not understand the origin of the matter of the biosphere, it is clear that it has been functioning in the same way for billions of years.[171] It is a mystery, just as life itself is a mystery, and constitutes a gap in the framework of our knowledge.

161 Preston Cloud (Cloud, 1983, p. 138) defined the biosphere as "a huge metabolic device for the capture, storage and transfer of energy."

162 Vernadsky emphasizes here how the energy from sunlight can penetrate downward into the crude matter of the biosphere as plant roots, deep soil microbes, the hot deep biosphere, etc.

163 Of, or pertaining to, ground water or the zone of water saturation in soil.

164 In his later work Vernadsky considered inert and biogenic matter separately. He defined the inert matter as "the matter created by processes in which living matter does not participate," and the biogenic matter as "matter which has been created and processed by life" (Vernadsky, 1965, pp. 58-60). Vernadsky had not yet made this distinction at the time of the writing of *The Biosphere*. For more details, see Lapo, 1987.

165 See Ocken, 1843.

166 See Steffens, 1801.

167 See Lamarck, 1964.

168 This paragraph relates directly to Vernadsky's main purpose in writing this book. He wanted to demonstrate the primacy of life as a geological force, and to show that life makes geology. Living processes have a fairly direct influence over, even control of, all crustal geological processes. Vernadsky was absolutely correct to emphasize this point, and this is exactly what makes *The Biosphere* such an important book.

169 Grace Osmer (McMenamin and McMenamin, 1994, p. 259) calculates the quantity of water in Hypersea to be 19 cubic kilometers, having a mass of 19 $km^3 \times (10^9 m^3/1 km^3) \times (10^6 cm^3/1 m^3) = 1.9 \times 10^{16}$ cm^3 or grams of water. This value represents a significant fraction of Earth's biomass. Vernadsky's mass of the biosphere (10^{24} grams) is hugely greater (by eight orders of magnitude) because it includes the bio-inert parts of the lithosphere as well as activated living matter. The actual amount of living matter is no doubt much less a fraction of one percent or two to three orders of magnitude difference than the estimate Vernadsky gives. This only serves to underscore Vernadsky's point about the geochemical, catalytic nature of life in the biosphere.

170 Vernadsky thus implies that any "azoic" period would have been pre-geological. Oparin (1957, p. 57-59) had much to say about this, and in the end exonerated Vernadsky for finally agreeing that life could have an origin:

"As a result of prolonged and varied studies of the question, we see that Vernadsky abandoned the untenable position of materialistic dualism [life distinct from other matter] which he previously held. In 1944 he wrote 'in our time the problem cannot be treated as simply as it could during the last century when, it seemed, the problem of spontaneous generation had finally been solved in a negative sense by Louis Pasteur's research.'"

Indeed the picture became more complex with Bernal's suggestion that absorption of organic molecules onto clays, assymetric quartz crystals or other minerals would provide for the concentration of molecules required for life's origin, and would prevent reverse reactions (Young, 1971, p. 371). In 1908 Vernadsky championed directed panspermia as support for the eternity of life:

"By the way, it turns out that the quantity of living matter in the earth's crust is a constant. Then *life* is the same kind of part of the cosmos as energy and matter. In essence, don't all the speculations about the arrival of 'germs' [of life] from other heavenly bodies have basically the same assumptions as [the idea of] the eternity of life." (see Bailes, 1990, p. 123).

Bailes (1990, p. 123) criticizes this passage as evidence of a "mystical strain" in Vernadsky's thought. Such criticisms were also levied by Oparin, who complained that Vernadsky's "theories of perpetual life" (p. 59) were not in accord with the "objective data of modern science." Although Bailes seems confused by Vernadsky's letter to Samoilov, the passage helps us now to clarify Vernadsky's thought in these matters. Vernadsky is in effect characterizing life as not merely a geological force but as a cosmic force on a par with energy and matter. Life for Vernadsky is not an epiphenomenon of matter in an energy stream but a comparably powerful entity in and of itself. Comparatively fragile in any given place and at any given moment, the true force of life is manifest over geologic time.

171 This remarkable passage captures the spirit of Part One of *The Biosphere*. In the same way that a geological system is a time-rock unit (all the rocks deposited during a certain interval of geological time), Earth's crust for Vernadsky becomes a life-rock unit, "saturated with life," and ultimately characterized by this life. Life for Vernadsky is the *sine qua non* of Earth's crust as we know it.
What came before on this planet is, just as it was in Vernadsky's time, still quite unknown. The Russian version of substantive uniformitarianism expressed here by Vernadsky has its own scientific validity. As we will see in Part Two, not only does Vernadsky's view permit Earth a history, it *requires* that the living matter of the biosphere develop (*razvitie*) to more complex states.