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INSIDE

Gaia and the Colonization of Mars

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Dedicated to the memory of Heinz A. Lowenstam (1913–1993)

ABSTRACT

The Gaia hypothesis states that the atmosphere, hydrosphere, surface sediments, and life of Earth behave dynamically as a single integrated physiological system. What has been traditionally viewed as the *passive environment is a highly active, integral part of the gaian system.* Aspects of the surface temperature and chemistry are regulated by the sum of life, the biota. Formulated first by James E. Lovelock, in the late 1960s, the Gaia hypothesis has been in the scientific literature for more than 25 years. Because of its properties of exponential growth and propagation, life is a powerful geologic force. A useful aspect of the Gaia idea is that it requires integration of scientific disciplines for the study of Earth. The recently touted Earth system science is broadly parallel with the gaian concept of the physiochemical regulation of Earth's surface. We discuss here, in a gaian context, the colonization of Mars by Earth organisms. Although colonizing Mars may be impossible, its accomplishment would be exactly equivalent to "the reproduction of Gaia by budding."

INTRODUCTION

The Gaia hypothesis of James E. Lovelock holds that the surface temperature, chemistry of the reactive gases, redox state, and pH of Earth's atmosphere and surface sediments are homeorrhetically maintained by the metabolism, behavior, growth, and reproduction of living organisms. (Homeostasis is physiological regulation around a fixed set point, like control of adult mammalian body temperature around 37 °C, whereas homeorrhesis, a parallel concept, refers to regulation around a changing set point, like temperature regulation in a developing mammalian embryo.) The term "Gaia," the name of a daunting Greek goddess, is, in Lovelock's view, simply "a good four-letter word referring to the Earth." She is also "Ge" or "Gaea" (e.g., the Geos satellite, geology, geography, or in Pangea).

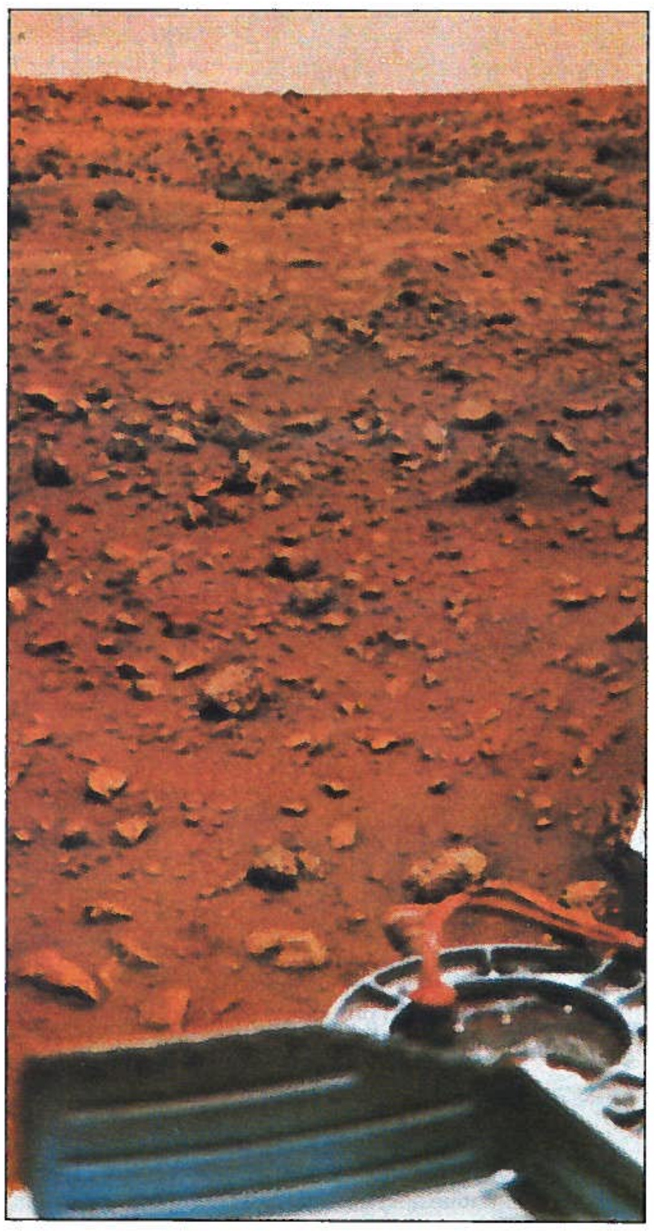

Figure 1. View of the Martian regolith from the Viking lander (in foreground). The surface is thought to be red from ferric iron.

Gaian environmental regulation is achieved largely by the origin, exponential growth, and extinction of organisms, all related by ancestry and physically connected by proximity to the fluid phases (water and air) at Earth's surface. Organisms in communities form changing ecosystems that have persisted since the Archean. The interactions of organisms, driven by solar energy, produce and remove gases such that chemistry of non-noble gases, temperature, and alkalinity are actively maintained within limits tolerable to life.

Within this conceptual framework, biological as well as physical sciences become appropriate to the analysis of Earth's atmosphere and geologic history. Especially pertinent is the role of the microbiota (bacteria, protoctista, fungi) in Earth surface gaseous exchange that involves the recycling of those chemical elements (e.g., H, C, O, N, P, S) absolutely required by life.

TABLE 1. PLANETARY ATMOSPHERES

	Venus	Earth	Mars
Carbon dioxide (%)	98	0.03	95
Nitrogen (%)	1.7 (ve)	79	2.7 (vi)
Oxygen (%)	Tr (ve)	21	0.13 (vi)
Methane (%)	none	0.0000015	none
Water (m*)	0.003	3000	0.00001
Pressure (atm)	90	1	0.0064
Temperature (K)	750	290	220

* Depth of water in metres over the planet if all water vapor precipitated out of the atmosphere.

THE GAIA IDEA

Product of the lively imagination of a British atmospheric chemist and the international space program, the Gaia idea has come of age. The atmospheric composition of Earth signals unmistakably that the third planet is living: flanked by the dry, carbon dioxide–rich worlds of Mars and Venus, one invokes either physiological science or magic to explain Earth's wildly improbable, combustive, thoroughly drenched troposphere (Table 1). The Gaia hypothesis, in acknowledging this atmospheric disequilibrium (Margulis and Lovelock, 1974) has opted for physiology over metaphysics.

More than 25 years worth of scientific contribution is listed in Appendixes 1 and 2; many scientists are unaware of the extent of the serious literature and the potential contribution of the Gaia idea for integrating evolutionary, meteorological, sedimentological, and climatological data. Unfortunately, nonscientific Gaia literature (which tends to be anti-intellectual and hysterically toned "New-Age" commentary) has received so much press attention and contentious comment that much of the primary science remains unknown.

Despite the fact that an "Earth system science" approach is vigorously encouraged for the solid-earth sciences, mention of the G-word (Gaia) still causes apoplexy in some scientific circles. This is remarkable, considering the broad parallelism of these approaches to understanding Earth processes. The U.S. National Academy of Sciences (NAS) (1993) report on future directions of research in the solid-earth sciences advocates "A new approach to studying Earth processes, in which the Earth is viewed as an integrated, dynamic system, rather than a collection of isolated components" (statement by Frank Press in his introductory letter). This report calls for an understanding through integrated study of physical and biological processes and sees as desirable a process-oriented global approach to understanding Earth. Despite avoidance of the term, a gaian approach is advocated by the NAS.

The Gaia hypothesis, rejected by some as the fantasy of New Age crystal swingers, has been largely misunderstood by the scientific community. For example, George C. Williams (1992) perpetuates confusion by unconscionably maligning Gaia: "It [the idea that the universe is especially designed to be a suitable abode for life in general and for human life in particular] had to be abandoned in its earlier forms with the triumph of Copernican astronomy ... but some scholars still find it possible to argue that the Earth, at least, can be regarded as especially suited for human life.... [The] main modern manifestation [of this idea] is in the gaia concept of Lovelock and Margulis (1974)."

The Gaia hypothesis demonstrates how life sciences are essential to understanding Earth, while revealing the inadequacy of evolutionary theory developed in the absence of climatological and geological knowledge. The gaian viewpoint is not popular because so many scientists, wishing to continue business as usual, are loath to venture outside of their respective disciplines. At least a generation or so may be required before an understanding of the Gaia hypothesis leads to appropriate research.

VIKINGS OF '76

When the Viking mission to Mars returned its data, some members of the scientific community thought that "planetary biology" or "exobiology"

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were doomed because the absence of Martian life rendered them sciences with no object of study. Lovelock and his colleagues thought just the opposite: now that data from Mars were available, speculations comparing the planets could be replaced with knowledge. It became certain that the bleak Martian landscape is devoid of life (Fig. 1), whereas life is not only a planet-wide phenomenon but in today's Solar System living beings are limited to Earth's biosphere.

Gaia has been called "Goddess of the Earth," or the "Earth as a single living being." These are misleading phrases. Since much scientific work mentioning Gaia suffers from problems of misunderstood terminology, we offer this physiologically oriented statement of the Gaia hypothesis:

GAIA AS EARTH'S ECOSYSTEM PHYSIOLOGY

The Gaia hypothesis states that the chemical composition of the reactive gases and the temperature of Earth's atmosphere are biologically controlled. Certain features, e.g., the salinity and alkalinity of the hydrosphere, are moderated by the biota (flora, fauna, and microbiota) in that their range of variation is kept within tolerable limits. Over 30 million types of live beings, descendants from common ancestors and members of five kingdoms, produce and remove gases, ions, and organic compounds. Their collective activity results in regulation of Earth's temperature and aspects of its surface composition: pH, oxidation state, etc. The chemical reactions of a physiology (unlike those of a strictly physicochemical system) are moderated by metabolism and growth. Without life, surface properties of Mars, Earth, and Venus would be extremely similar: abundant in carbon-dioxide with a small proportion of gaseous nitrogen and very dry, reflecting their history, bulk composition, surface materials, proximity to the Sun, and interaction with solar radiation.

We reject the analogy that Gaia is a single organism, primarily because no single being feeds on its own waste nor, by itself, recycles its own food. Much more appropriate is the claim that Gaia is an interacting system the components of which are organisms. Nowhere is this more evident than in examples of biotic influence on important geological processes (Table 2; Westbroek, 1991).

The two landers and orbiters of the 1975–1976 Viking missions to Mars yielded data that complemented earlier Earth-based observations of that planet. Organic compounds were absent: the concentration of total organics if present must be less than one part per billion. The gas-chromatographic detection of oxygen was not due to life but to the release of O_2 from moistened peroxides, and the incorporation of radioactive CO_2 was due to cosmic radiation, including UV photochemistry, and not to photosynthesis. Once the reactants were spent, no new change was detected by these experiments. The conclusion is inescapable: no evidence exists for present life on Mars. The same is true of Venus.

As far as we know, the Gaia phenomenon is limited to Earth. Can it be extended by colonization of Mars? Comparison of Earth with Mars helps highlight both the nature of Gaia and implications of the idea for the study of Earth.

EXTRATERRESTRIAL GERMS

To prevent both lunar and Martian spacecraft from carrying microbes, "clean-room" techniques were applied. Even sterilization of the outside and much of the inside of the Viking spacecraft was undertaken. Ethylene oxide gas flooded the accessible components to assure microbial cleanliness; this increased the total cost of the Viking mission by about 10%. During the U.S. Apollo missions to the moon in the 1960s and 1970s, fears of possible "back-contamination" were rampant: extraterrestrial "germs" might "contaminate" Earth. This issue is sure to arise again if there is any future return of materials from Mars. Such fears seem silly, more a manifestation of pulp science fiction than a well-reasoned treatment of scientific probabilities.

Although investigators such as Rothschild (1990) have suggested that Martian life may still be found in oases, perhaps as permafrost bacteria or even as "endoevaporites" in isolated salt crystals, the chances of finding isolated life there are vanishingly small.

The Gaia hypothesis provided a framework for evaluation of Martian results. Life maintains its immediate environment and appears on Earth only as a planet-wide phenomenon. Life may have been sparse when it first appeared or may be sparse when it is dying out, as Lovelock emphasizes, but between these two end points life must be luxuriant. Why? Because of life's intrinsic tendency to grow, expand, and populate at exponential rates and its ability to travel. Therefore, a question of the 1990s is, Can life expand to

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TABLE 2. BIOLOGICALLY MEDIATED GEOLOGIC PHENOMENA

Example	Importance*	Lithospheric Reservoirs and Examples
1. Phosphorus cycle	Essential for all life: component of DNA and RNA nucleic acids and ATP and NADPH nucleotides; phospholipid membranes and the calcium phosphate of bones. Because phosphate is a major growth-limiting nutrient, the P cycle is completely biologically mediated. (Brock et al., 1982; Filipelli and Delaney, 1992)	Earth's crust (inaccessible to life) and deep-sea sediments; guano islands Atmospheric phosphine (PH_3) is negligible.
2. Calcium-carbonate deposition	Essential for formation of hard parts in shelled marine animals and many testate protoctists, e.g., foraminifera. Helps maintain pH balance in the oceans. As limestone, it is an important sink for CO_2.	Stromatolites Coral reefs Deep-sea carbonate ooze (foraminifera and coccoliths)
3. Organic matter deposition	Leads to development of anoxic conditions and CH_4 production, so that carbon is released to the atmosphere, thus preventing complete loss from the biosphere, leading to maintenance of elevated O_2 levels (Watson et al., 1978). Fossil fuels	Oil shale and other organic-rich shales Coal, peat, oil, tar sands
4. Methanogenesis	Atmospheric composition of Earth (e.g., presence of methane, ozone) is inexplicable in the absence of life. (Watson et al., 1978; Table 1)	Trapped natural gas, swamp and marsh gas Arthropod intestines Vertebrate rumen
5. Regolith consolidation	Unconsolidated sediments are bound by biotic communities, e.g., mucilage coating of bacterial mats. (Margulis and Stolz, 1983)	Mud Unlithified sediment
6. Erosion acceleration	Weathering rates increased by biologically mediated erosion, bacterial endoliths, fungal hyphae, plant roots, and lichens.	Lithosphere-atmosphere-hydrosphere interfaces
7. Microbially mediated mineral formation (biomineralization)	Genesis of important mineral deposits. Interpretation of modern and ancient environments.	Banded iron formation Witswatersrand gold deposits Bog iron Rock varnish Manganese nodules

*For references not in References Cited list, see Appendix 1 or 2.

Mars? This question, Can Mars be colonized?, is identical to that of, Can Gaia reproduce?

All organisms are connected through the atmosphere, and life as we know it on Earth is a global phenomenon, utterly dependent on sunshine. Hardy terrestrial forms such as halophiles or sulfur-loving acidophilic archaebacteria, ammonia-oxidizing chemolithotrophs or carbonate-precipitating stromatolite-forming cyanobacteria, are extremes connected to, and tolerated by, a ubiquitous planetary biota. There are no virtuoso individualists. Martian life, if present, would by analogy to Earth most likely be found in communities.

Although it is theoretically possible that subvisible life will be found in the nether reaches of Martian deserts, it remains far more likely that the Martian wasteland is as dead as it appears. If so, one scientific challenge is to enact in reverse the very process that was once so feared: to deliberately contaminate or, as is now said, to "seed" Mars with life from Earth.

ECOPOIESIS

The quest for life on Mars began (by telescope) long before the Viking missions, and it will not likely end with the deployment of rovers on the planet early in the next century. After acceptable confirmation that Mars is uninhabited, the next task might be to "seed" the red neighbor with propagules from Earth. (Many will justifiably argue that the resolution of more pressing Earth-based problems should be a far greater priority: curbing the human tendency to convert the surface of Earth to urban ecosystem or fostering and documenting the diversity of life.)

The first and perhaps most crucial task in making Mars habitable is to increase its surface temperature. Proposals for heating Mars have ranged from engineering dreams of melting the ice caps with giant orbiting mirrors or covering the surface with black lichens, to schemes of rocketing greenhouse chlorofluorocarbons (CFCs) into the atmosphere. Recent proposals tend to be more detailed and slightly more feasible, yet share with their forerunners a profound, simultaneous strength and weakness: although such schemes are ambitious enough to excite the imagination, making captivating layouts in popular science magazines, they are too grandiose and vague to be practical (Kluger, 1992).

For example, even if several millions of tons of new, UV-resistant CFCs could be produced annually in situ from the surface of Mars, leading to a release of carbon dioxide and to planetary temperatures of 22 °C, then what? Even if oceans appeared from ice trapped in the lower latitudes because a way had been found to return to the atmosphere the CO_2 now trapped in surface carbonates, what now? The density (and therefore livability) of a Martian atmosphere is probably intrinsically limited by the weakness of Mars's magnetic field. In the absence of magnetic deflection of solar wind a Martian atmosphere would quickly be ablated. Even if genetically engineered plants and microbes were created to produce oxygen and other gases at hitherto miraculous rates, it still could take, as Christopher McKay (NASA Ames Research Center) estimates, about a thousand years to build an atmosphere to stable levels of oxygen in carrier gases breathable by eukaryotic microbes, let alone humans.

Although the new science of geophysiology and the success of biotechnology with microorganisms may have incited us to fantasies of planetary design, colonizing Mars so that humans might walk in the open along its canyons remains a distant fantasy. One should distinguish here between ecopoiesis (Haynes, 1990, 1992; the inundation of a formerly uninhabited surface with viable living systems) and terraformation (McKay, 1987; the recreation of Earth on another planetary surface). For the foreseeable future, ecopoiesis but not wholesale terraformation seems a possibility for Mars; the former is, however, a prerequisite for the latter (McKay et al., 1991). Ecopoiesis would not make Mars into an extraterrestrial paradise, so much as it would transform it into a global cesspool—colorful, perhaps, but rich in mephitic vapors. The early history of Earth, after all, and the present state of the gas giants in the outer Solar System are characterized by a chemistry that more resembles sewer gas than food. Though alien and inhospitable to mammals, these reduced sulfurous carbon-rich volatile compounds were crucial to the origin and early evolution of life.

The only dependable way to make a planetary surface livable may be to repeat the evolutionary colonization process that occurred on Earth, which began with hydrogen, methane, ammonia, formaldehyde, sulfides, nitriles, and simple sugars. Shortly after life appeared, noxious gas exchanges among anoxygenic phototrophic bacteria and their dependents ensued. Sped up on Mars, the outcome of a rushed and deliberate Martian colonization process is likely to be highly unpredictable—possibly even tragic.

Will we humans, Godlike, wave our wand? Do we really think, in our naivete, that strewing our scientific instrumentation over the red surface of Mars via robots in a geological wink of an eye will produce a New Blue Earth? Far more probably, Mars will be colonized slowly and gradually, and not by humanity but through humanity, facilitated by robots. For the foreseeable future it seems likely that the only human presence on Mars will be via the developing technology of telepresence. The landing of the two remote-sensing, remote-controlled, human-connected Viking landers in 1976 proves that the process of colonization has already begun. Unlike Neil Armstrong's epochal "one step for man, one giant leap for mankind," the ecopoiesis of Mars's surface has no instantly recognizable moment. The launch of human-built life detectors to Mars, the "telepresent" sensory cameras that radio their signals back to eager humans at mission control, space-crew first landings, early orbiting Mars stations, and the eventual habitation of the red surface by emigrants of a variety of species—all are part of a gradual process of ecopoiesis. All would be likely to occur haphazardly, with very little conscious planetary bioengineering.

The distinction between altering one's body to "adapt" to any inhospitable environment and altering the environment itself is largely specious from a gaian viewpoint. As organisms evolve, both their bodies and the environment change irreversibly. Such change occurs through technology, which is not a uniquely human phenomenon. Animate and inanimate nonhuman technologies abound, e.g., wasp nests, humidified and air-conditioned termite mounds, or the

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Through the generosity of W. Storrs Cole, two awards for support of research are offered through GSA. The Gladys W. Cole Memorial Research Award provides research support for the investigation of the geomorphology of semiarid and arid terrains in the United States and Mexico. It is to be given to a GSA Member or Fellow between 30 and 65 years of age who has published one or more significant papers on geomorphology. Funds cannot be used for work already accomplished, but recipients of a previous award may reapply if additional support is needed to complete their work. The amount of this award in 1994 will be $7000.

The second award, the W. Storrs Cole Memorial Research Award, has been established to support research in invertebrate micropaleontology. This award will also carry a stipend of $7000 and will be given each year to a GSA Member or Fellow between 30 and 65 years of age who has published one or more significant papers on micropaleontology.

Additional information and application forms may be obtained from June R. Forstrom, Research Grants Administrator, GSA, P.O. Box 9140, Boulder, CO 80301.

All applications must be postmarked on or before February 15, 1994. Actions taken by the Committee on Research Grants will be reported to each applicant in early April.

These are two of GSA's most prestigious awards; all qualified applicants are urged to apply.

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immense lithified limestone reefs fringing tropical islands.

GAIA'S PROPAGULES

Life packages its precious contents: production of heat-proof bacterial endospores, dinomastigote cysts, formation by trees of seeds and hardened fruits, rubbery eggs of snakes, or the tough eggcases of rays. Among the most remarkable of such propagules are the "tuns" of tardigrades or the salt-tolerant dust-like eggs of brine shrimp (Fig. 2).

To enable any Earthlings to dwell on the surface of Mars, bubblelike enclosures probably will be required that house a complexity of species in self-supporting recycling systems, in principle like the stated goals of the exorbitant Biosphere II project in Arizona's Sonoran desert. This incipient Earth-propagule (which "germinated" and released its contents in September 1993) contained eight "biospherians." The 17-acre facility allegedly was "materially closed" in the autumn of September 1991 to all but its enormous intake of external electrical power. It is clear that at present we are far from establishing any biospheres on Mars. The energy needed for the mere sustenance of any biospheres let alone their use as bases for any bio-industrial modification of the planet, will require on-site nuclear power. However, as soon as adequately closed artificial biospheres are established—e.g., to serve as base camps for CFC factories—global, terrestrial, biospheric Earth life will have de facto, if inconspicuously, colonized the surface of Mars.

Such an artificial biosphere, a radiation and desiccation-resistant form, is highly reminiscent of large-scale non-human evolutionary innovations far more continuous with the past than it seems at first glance. By packaging and miniaturizing the essentials for survival, life ventures out upon and ultimately makes a home for itself in formerly hostile terrain.

The ecopoiesis of Mars would likely be accomplished by interaction of many types of Earth organisms: bacteria, protoctists (mainly as algae), plants, and fungi will certainly play their roles. Indirectly, all life forms would be involved in planetary colonization, although at first multispecies bases will need to be constructed in an effort planned by exceedingly few, highly select, and passionately dedicated humans. Such bases are necessary to protect their inhabitants from an initially hostile external Martian world. Food plants must be grown and all wastes internally recycled.

That such enclosures of metal, glass, and plastic might be built by scientists, engineers, and other working people is hardly an argument for their absolute uniqueness: all previous technological advances in the evolution of life (e.g., silica fretwork of diatoms, calcium phosphate bone and teeth in vertebrates, lignification leading to great height in plants, and the chitinous exoskeletons of insects and crustaceans) involved more than a single type of life and were prerequisite to the adaptive radiation of their inventors into new and formerly hazardous realms.

Humans by no means have an "exclusive" on technology. Magnetite teeth in molluscs and wax synthesis by hymenopterans are technologies that preceded those of *Homo sapiens* by millions of years. Calcium phosphate teeth, barium sulfate gravitational sensors, and temperature- and humidity-controlled termite mounds were as much a prerequisite for cosmopolitan Cenozoic distribution of, say, rodents, charalean algae, and fungi-gardening termites as telephones and electric power are to human urban expansion. Silurian-Devonian emigration of life to the land, with its attendant problems of lack of support by water, depleted nutritional substrates, and its exposure to continuous solar UV radiation, demanded a dramatic repackaging of life's resources—an incorporation into bodies of what at one time could be found only "outside"—in the mineral environment (Sagan, 1992).

Such repackaging of living beings and their accoutrements might begin within recycling enclaves, "artificial biospheres." Above and beyond anything done later, the first of these bases on Martian terrain would already be colonization of Mars. Cosmic historians, in retrospect, might use establishment of such Martian base camps to date the reproduction of planetary life. Such "artificial biospheres" might be recognizable not merely as a human technology but as an expansion and metamorphosis of Earth's original biosphere by members of all of the five kingdoms of life (Fig. 3). Gaia would have reproduced, challenging the objection of Doolittle (1981) that Gaia cannot be a life form because it is incapable of reproduction. Seen from afar, the settling of Mars would be akin to budding, a space-borne planting of a

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Figure 2. Propagules: clockwise from top left, bacterial endospores, dinomastigote resting cysts (in paleontological literature as hystrichospheres), walnuts, and possible future biosphere.

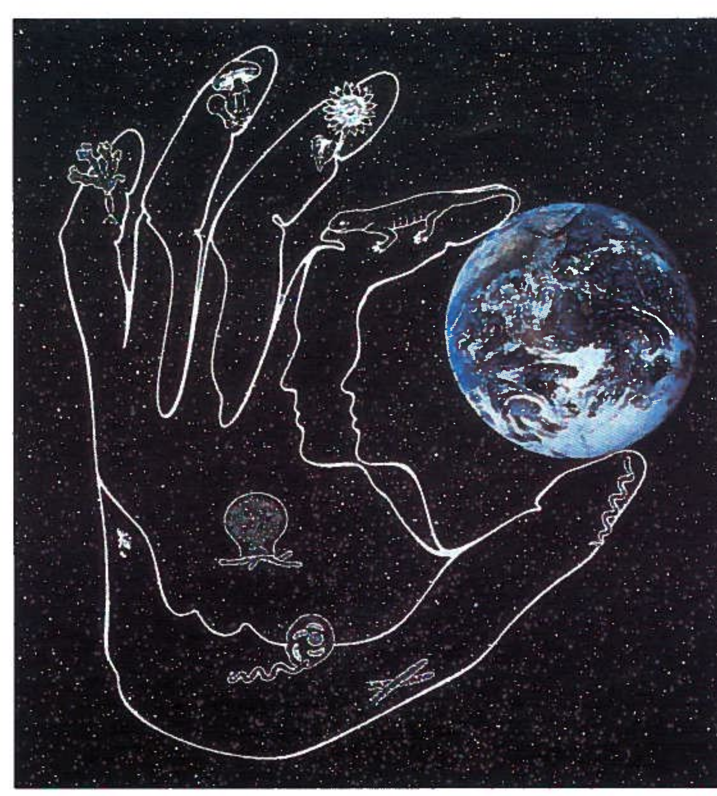

Figure 3. Five kingdom hand representing the major forms of life all connected through nearly four billion years of "Darwinian time" at Earth's surface ("Vernadskyian space"). In order of appearance (Ga—billion years ago) in the fossil record: Monera (Bacteria or prokaryotae, 3.9 Ga), Protoctista (algae, slime molds, ciliates and other microscopic eukaryotes and their larger descendants, 2 Ga), Animalia (egg-sperm embryo forming diploids, 0.75 Ga), Fungi (zygo-, asco-, basidiomycota, fungi imperfecti, and lichens that grow from fungal spores, 0.45 Ga), Plantae (bryophytic or tracheophytic haplodiploids that develop from maternally retained embryos, 0.45 Ga). This illustration is from the cover of *Five Kingdoms: An Illustrated Guide to the Phyla of Life* (second edition) by Margulis and Schwartz, 1988. (Available as a teaching unit from Ward's Natural History Establishment, Rochester, New York.)

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"sporulated" form of biospheric life—Gaia transporting propagules of itself to the surface of a new world.

CONCLUSIONS

A gaian scientific world view is especially relevant in light of extensive human-wrought modification of the global environment and the talk about further missions to Mars. Although the fundamentals of Lovelock's Gaia hypothesis have not changed in 25 years, researchers still don't yet understand them. The gaian approach critically enables research on Earth systems precluded by the patchiness of the "academic apartheid" from which Lovelock, as a young man, fled.

The gaian concept of physiological surface regulation is unpalatable, especially to those who hold dogmatic ideas on Earth processes. Lovelock remarked (in the BBC program "Goddess of the Earth") that the Gaia hypothesis hasn't been controversial; it has just been ignored. But the scientific details, contained in the literature listed here (Appendix 1), are becoming better known. We are hopeful that the full importance of the Gaia idea will continue to be more extensively understood by scientists and students, especially by geologists upon whom rest the future of gaia-oriented scientific research.

ACKNOWLEDGMENTS

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APPENDIX 1. PROFESSIONAL LITERATURE ON GAIA

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