Gaia and the Colonization of Mars
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Dedicated to the memory of Heinis 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 old concept of the physicochemical 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 homeothermically 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 homeorhesis, 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 Pangae).

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, protistota, 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. The Gaia idea

TABLE 1. PLANETARY ATMOSPHERES

<table>
<thead>
<tr>
<th></th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (%)</td>
<td>98</td>
<td>0.03</td>
<td>95</td>
</tr>
<tr>
<td>Nitrogen (%)</td>
<td>1.7 (ve)</td>
<td>79</td>
<td>2.7 (v)</td>
</tr>
<tr>
<td>Oxygen (%)</td>
<td>19 (ve)</td>
<td>21</td>
<td>0.13 (v)</td>
</tr>
<tr>
<td>Methane (%)</td>
<td>none</td>
<td>0.0000015</td>
<td>none</td>
</tr>
<tr>
<td>Water (m³)</td>
<td>0.003</td>
<td>3000</td>
<td>0.00001</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>150</td>
<td>1</td>
<td>220</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>750</td>
<td>290</td>
<td>220</td>
</tr>
</tbody>
</table>

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

Lovelock, 1974) has opted for physiology over metaphysics. Since that 25 years worth of scientific contribution is listed in Appendices 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 unconditionally maligning Gaia: "[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 "exo-biology"...
Gaia continued from p. 277

were doomed because the absence of Martian life rendered them sciences with
no object of study. Lovelock and his colleagues argue just the oppo-
site: that now that data from Mars were available, speculations comparing
the planets could be replaced with knowl-
dge. 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
altitudes of the hydros- 

phere, are moderated by the biota (flora, marine, and microbionota) in
that their range of variation is kept within tolerable limits. Over 20 million
types of living

beings, descendants from common ancestors and members of five
groups, produce and recycle gases, ions, and organic compounds.
Their collective activity acts in regulation of Earth's temperature and
aspects of 
surface composition: pH, oxidation states, and chemical
reactions of a physiology (those of a strictly physicochemical system)
are moderated by metabolism and growth. Without life, surface properties of
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 composi-
tion, 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 proces-
ses (Table 2; Woytowich, 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 detect-

ions of radioactive CO2 due to cosmic radiation, including UV photchemis-

try, and not to photosynthesis.

Once the reac-
tants were spent, no new change was detected by these experi-

ments. The conclusion is inescapable: no evidence of life exists for present

life on Mars. The same is true for 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 impli-
cations 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 "con-
taminlate" 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 sci-

ence fiction than a well-reasoned treat-

ment of scientific probabilities.

Although investigators such as

Rothschild (1990) have suggested that Martian life may still be found in oases,

perhaps as pensemble bacteria or even "endovandecous" 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 have been sparse when it is dying out, as Lovelock emphasizes, but both between these two endpoints life must be luxuriant. Why? Because of life's intrinsic tendency to grow, expand, and populate at stationary or exponential rates and its ability to travel. Therefore, a question ex-
ished by the study of Gaia.

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**TABLE 2. BIOLOGICALLY MEDIATED GEOLGIC PHENOMENA**

<table>
<thead>
<tr>
<th>Example</th>
<th>Importance*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Phosphorus cycle</td>
<td>Essential for all life: component of DNA and RNA nucleic acids and ATP and NADPH nucleotides; phospholipid membranes and the calcium phosphate of bones</td>
</tr>
<tr>
<td>2. Calcium-carbonate deposition</td>
<td>Essential for formation of hard parts in shell-forming animals and many microbe-associated life-forms, e.g., foraminifera. Helps maintain pH balance in the oceans. As limestone, it is an important sink for CO2</td>
</tr>
<tr>
<td>3. Organic matter deposition</td>
<td>Leads to development of anoxic conditions and CH4 production, so that carbon is released to the atmosphere, thus preventing complete loss from the biosphere, leading to maintenance of elevated O2 levels (Watson et al., 1978). Fossil fuels</td>
</tr>
<tr>
<td>4. Methaneogenesis</td>
<td>Atmospheric composition of Earth (e.g., presence of methane, ozone) is inescapable in the absence of life. (Watson et al., 1978; Table 1)</td>
</tr>
<tr>
<td>5. Regolith consolidation</td>
<td>Unconsolidated sediments are bound by iron oxide coagulates, e.g., a clayey coating of bacterial mats. (Margulis and Stolz, 1983)</td>
</tr>
</tbody>
</table>
| 6. Erosion acceleration | Weathering rates increased by biologically mediated erosion, bacterial endoliths, fossil g

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*For references not in References Cited list, see Appendix 1 or 2. 278

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**GSA TODAY, November 1993**
Gaia continued

Although the new science of geophysiology and the success of biotechnology with microorganisms may have incited us to envision planets 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 eco- poiesis (Haynes, 1990, 1992), the intrinsic design of a living uninhhabited surface with viable living systems) and terraformation (McKay, 1987): the re-creation of Earth on another planetary surface. For the foreseeable future, eco- poiesis but not wholesale terraformation seems a necessary first step. 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 seascape—colorful, perhaps, but rich in mephitic vapors. The early history of Earth, after all, and the present state of the gas giant Titan indicate that the Martian system are characterized by a chemistry that more resembles sewer gas than food. Though alien in composition to mammals, these reduced sulfur-rich carbon-rich volatile compounds were crucial to their own and early stage convol- lution 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 life. Methane, ethane, acetylene, methane, formaldehyde, sulfides, nitriles, and simple sugars. Shortly after life appeared, it was capable of exchanging gases among anoxic phototrophic bacteria and their descendants. Sped up on Mars, the outcome of this rushed and deliberate Martian coloni- zation process is likely to be highly unpredictable, possibly even tragic.

If we humans, Godlike, wave our way through the stars, we might think, in our naivete, that stewarding our scientific in- strumentation over the red surface of Mars is more important than a geological eye will produce a New Blue Earth, far more likely. Mars will be colo- nized slowly and gradually, and not by humanity but through humanity, facilit- ated by robots. For the foreseeable future it seems likely that the only hu- man 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 epochs of Mars’s sur- face has no instantly recognizable moment. The launch of human in- cubators was an event, but the “telepresence” of sensory cameras that radio their signals back to eager humans at mission control, space-craft first landings, early orbiting Mars stations, and the even- tual habitation of the red surface by emigrants of a variety of species—all are part of a gradual process of eco- poiesis. All would be likely to occur haphazardly, with very little conscious planetary bioengineering.

The distinction between altering one’s body to “suit” any inhospitable environment and altering the environment itself is largely specious from a gain viewpoint. As organisms evolve, both their bodies and the envi- ronment change irreversibly. Such change occurs through technology, which is not a uniquely human phe- nomenon. Animate and inanimate nonhuman technologies abound, e.g., wasp nests, humidified and air- conditioned termite mounds, or the...

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Posi tion Available

The Geological Society of America is seeking an earth scientist with proven managerial experience and achievements, general familiarity with GSA programs, and a working knowledge of the publication business to assume the position of Executive Director in June 1994 when Dr. F. Michael Wahl will retire.

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Cole Memorial Research Awards in Geomorphology and Micropaleontology

Through the generosity of W. Stuarts Cole, two awards for support of research are offered through GSA. The Gladys W. Cole Memorial Research Award provides research support for the exploration 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.

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All applications must be postmarked on or before February 15, 1994. Applications 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.
IMMENSE LITTORAL LIMESTONE REEFS FRINGING TROPICAL ISLANDS

GAIA'S PROPAGULES

Life packages its precious contents: production of heat-proof bacterial endospores, dinoflagellate cysts, forma-
tion 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 “tubs” or “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 “biophototrophs.” 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 biosphere that are capable of producing food or providing another use of bases for any bio-industrial modifi-
cation 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 CFCC factories—global, terres-
trial, biospheric Earth life will have de facto, if inconspicuously, colonized the surface of Mars.

Such an artificial biosphere, a radiol-
ation 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 sur-
vival, life ventures out upon and ulti-
mately makes a home for itself in for-
merly hostile terrain.

The ecopoets of Mars would likely be accomplished by interaction of many types of Earth organisms: bacteria, prototists (mainly as algae), plants, and fungi will certainly play their roles. Indirectly, all life forms

would be involved in planetary colo-
nization, although at first multispecies bases will need to be constructed in an effort planned by exceedingly few, highly select, and passionately dedi-
cated 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 sci-

Figure 2. Propagules: clockwise from top left, functional endospores, dinoflagellate resting cysts (in paleontological literature a heterospherom), walnuts, and possible future biosphere.