Gaia by Any Other Name

Lynn Margulis

We upright, nearly hairless, chatty chimps owe our burgeoning population numbers to our flexible brains and our intense social behavior. All of us can attest to the strength of cultural and linguistic influences between birth and say, twenty years of age; words and symbols are powerfully evocative and may even stimulate violent activity (Morrison, 1999). Examples of symbolic emotion-charged phrases abound. In today's political realm they include "evil Middle East dictator," "HIV-AIDS victim," "neo-Nazi," "genetically manipulated crops," "dirty nigger," "one nation under God," "drug addicts," "white supremacist," "sexual abuser," and many far more subtle others.

Science, ostensibly objective and free of such name-calling, is not immune. Although to most of the contributors to this book, "science" simply refers to an open, successful, international, and cooperative means of acquiring new knowledge by observation, measurement, and analysis, to many outsiders "science" is an emotion-charged term. To some it implies atheism, triviality, lack of patriotism, or willingness to collaborate with huge corporations against their workers. To others a scientist is someone deficient in empathy or lacking in emotional expression or, worse, a supplier of technical know-how complicit in the development of weapons of mass destruction.

Here, following James E. Lovelock's lead in his accompanying piece "Reflections on Gaia," as someone proud to participate in the international scientific effort, I mention the impetus to new investigations. The "Gaia hypothesis" has now become the "Gaia theory" and has given voice to disparately trained researchers over the last few decades.

The very beginning of the Gaia debate, I submit, was marked by a little-known *Nature* paper (Lovelock, 1965). Gaia's middle age, her 40th birthday, ought to be celebrated with appropriate fanfare in or near the year 2005. Such recognition would mark the anniversary of the widespread dissemination of her gorgeous dynamic image. Photographed and made well known by Russell (Rusty) Schweikart and especially as the "blue marble" (the living Earth seen from space) taken by the 1968 circumlunar Apollo 8 team (Frank Borman, Jim Lovell, and Edward Anders), the image generated a gaggle of Gaia enthusiasts. From the beginning Gaia's intimate portrait has been delivered to us by these and lesser fans of outer space, most of whom were interviewed by Frank White (1998). Indeed, close-ups of her green and mottled countenance are newly available in the spectacular full-color, oversized book that reveals Gaia from above (Arthus-Bertrand, 1999).

To me, the Gaia hypothesis, or theory as some would have it, owes its origin to a dual set of sources: the immense success of the international space program that began with the launch of *Sputnik* by the Soviet Union in 1957 and the lively but lonely scientific imagination, inspiration, and persistence of Jim Lovelock. Part of the contentiousness and ambiguity attendant on most current descriptions of the Gaia hypothesis stems from confused definitions, incompatible belief systems of the scientific authors, and inconsistent terminology across the many affected disciplines (for example, atmospheric chemistry, environmental studies, geology, microbiology, planetary astronomy, space science, zoology). Anger, dismissive attitude, and miscomprehension also come from the tendency of the human mind toward dichotomization. In this limited summary whose purpose is to draw attention to several recent, excellent books on Gaia science and correlated research trends, I list the major postulates of the original Gaia statement and point to recent avenues of investigation into the verification and extension of Lovelock's original ideas. I try to minimize emotionally charged rhetoric aptly indulged in and recently reviewed by Kirchner (2002) and to maximize the proximity of the entries on my list to directly observable, rather than computable, natural phenomena. I self-consciously align this contribution to a field ignored by most of today's scientific establishment and their funding agencies, one considered obsolete, anachronistic, dispensable, and atavistic. To me this field in its original form, "natural theology" that became "natural history," should be revived with the same enthusiasm with which it thrived in the 18th and early 19th centuries.

That age of exploration of the seas and lands generated natural history in the same way that satellite technology and the penetration of space brought forth Gaia theory. In fact when Lovelock said, "People untrained ... do not revere ... Geosphere Biosphere System, but they can ... see the word Gaia embracing both the intuitive side of science and the wholly rational understanding that comes from Earth System Science" he makes a modern plan for the return to the respected natural history, the enterprise from which biology, geology, atmospheric science, and meteorology had not yet irreversibly divorced themselves. Is he not explicit when he writes, "We have some distance still to travel because a proper understanding of the Earth requires the abolition of disciplinary boundaries"? For the science itself, although precluded today by administrative and budgetary constraints, the advisable action would be a return to natural history, the status quo ante, before those disciplines were even established. As Lovelock says, and I agree, "We need reduction in science, but it is not the whole story." My point is that yes, I agree, reductive simplification to control one variable at a time is indispensable to scientific inquiry. Yet no reason exists for us not to continue reductionist practices in the context of Gaian natural history. Indeed, the name changes ought not to deceive us about the true identities of our friends. "Astrobiology" is the field of natural history reinvented to be fundable for a wide variety of scientists, whereas "Earth system science" is none other than Gaia herself decked in futuristic garb and made palatable to the "hard rock" scientists, especially geophysicists.

The original Gaia hypothesis primarily involved biotic regulation of three aspects of the surface of the Earth: the temperature, the acidity-alkalinity, and the composition of the reactive atmospheric gases, especially oxygen. Accordingly I tentatively offer an adequate working definition of the Gaia hypothesis that can serve to organize an enormous, unwieldy scientific literature. Gaia, a name that makes our third planet, as Lovelock likes to say, "a personal presence for all of us" refers to the science of the living Earth as seen from space. My definition for the Gaia hypothesis is as follows:

> Some 30 million types of extant organisms [strains of bacteria and species of eukaryotes; Sonea and Mathieu, 2000] have descended with modification from common ancestors; that is, all have evolved. All of them—ultimately bacteria or products of symbioses of bacteria (Margulis and Sagan, 2002)—produce reactive gases to and remove them from the atmosphere, the soil, and the fresh and saline waters. All directly or indirectly interact with each other and with the chemical constituents of their environment, including organic compounds, metal ions, salts, gases, and water. Taken together, the flora, fauna, and the microbiota (microbial biomass), confined to the lower troposphere and the upper lithosphere, is called the biota. The metabolism, growth, and multiple interactions of the biota modulate the temperature, acidity-

alkalinity, and, with respect to chemically reactive gases, atmospheric composition at the Earth's surface.

A good hypothesis, as Lovelock has noted, whether or not eventually proved right or wrong, generates new experimental and theoretical work. Gaia, defined this way, undoubtedly has been a good hypothesis. Gaian concepts, especially in the 1980s and early 1990s, generated an environmental literature (Lapo, 1987; Lovelock, 1979, 1988; Sagan, 1990; Westbroek, 1991) that extends far beyond the bounds of the traditional relevant subfield of biology: "ecology." Ecology as taught in academic circles has become more Gaian or has faded away.

Of particular interest to me is "new Gaia," newly generated scientific ideas beyond the original statement of the theory. Several are worthy of closer scrutiny by observation, experimentation, and model calculation. New books to which I refer (Lowman, 2002; Morrison, 1999; Smil, 2002; Sonea and Mathieu, 2000; Thomashow, 1996; Volk, 1998) have done us a great service by review and interpretation of jargon-filled incommensurate scientific articles. These authors provide an essential prerequisite for future investigation. In the case of Thomashow (1996), the review is less of the science and more of the history and emotional importance of Gaian concepts in the context of environmental education and ecological understanding.

In this necessarily brief contribution to what Lovelock sarcastically refers to as his "weak little theory," some predictions have been confirmed. Thus, I concur with the ten items on Lovelock's list, but I concentrate on other "new Gaia" aspects of the science. For discussion I especially question the Earth's relation to the phenomenon of continental drift and plate tectonics.

"Surface conditions on Earth," NASA geologist Lowman (2002) writes, "have been for most of geological time regulated by life." Lowman identifies this statement as Lovelock's Gaia hypothesis and claims, "This new link between Geology and Biology originated in the Gaia hypothesis" (p. 272). The Gaia concept leads Lowman to a new perspective on the evolution of the crust of the Earth and to his "unified biogenic theory of the Earth's crustal evolution," which will be defined here.

Lowman's synthesis derives the earliest events in our planet's evolution from those which surely occurred on our lifeless solar system neighbors: the Moon, Mercury, and Venus. The new science of comparative planetology is generated by many studies, especially the use of the superb new tools of space geodesy, satellite measurements of geomagnetism, remote sensing across the electromagnetic spectrum, and analyses of impact craters. This new work leads Lowman to a radically different view of Earth's tectonic history. He posits that the Earth's major concentric layers—the liquid core, the convecting plume-laden mantle, and the cooler, more rigid outer crust—were formed by the same processes that occurred on our neighboring silicate-rich planets. Such planetary and petrologic processes preceded Gaia. The main crustal dichotomy of an Earth divisible into the two regions (generally granitic continental masses and basaltic ocean basins), he argues, was initiated by the great early bombardment scenario of the inner solar system. The Earth, like its neighbors, was so beset by bolides that the crust was punctured and heated time and again. Incessant volcanism was intense on an Earth far hotter and tectonically more active than today. Two-thirds of the primordial global crust may have been removed by the giant impact of a Mars-sized bolide that ejected the debris from which our huge satellite, the Moon, accreted. The so-called lunar birth explosion, he thinks, may have triggered mantle upwelling, basaltic magmatism, and tectonic activities similar to "those of the Moon, Mercury, Mars, and possibly Venus" (p. 279). However, "the broad aspects of the Earth's geology as it is now—continents, ocean basins, the oceans themselves, sea floor spreading and related processes—are the product of fundamentally biogenic processes, acting on a crustal dichotomy formed by several enormous impacts on the primordial Earth.''

Lowman goes on to claim, ''The fundamental structure of the Earth, not just its exterior and outer layers, thus appears to have been dominated by water-dependent—and thus life-dependent—plate tectonic processes.'' Life has actively retained water and moderate surface temperatures, not just passively ''adapted'' to them. In summary of many detailed investigations and their interpretations, Lowman writes:

> The most striking characteristic of the Earth is its abundant water: colloidally suspended in the atmosphere; covering two-thirds of its surface; coating, falling on, and flowing over the remaining one-third; and infiltrating the crust and mantle. It retains this water partly because of the planet's surface temperature but also because the Earth behaves like a living organism that maintains this temperature by a wide variety of feedback mechanisms, many of which are caused by life itself. (p. 280)

Presenting an integrated view of energy flow, oceanography, and climatology with the physics, chemistry and biology of the biosphere we all call home, Vaclav Smil, a distinguished professor at the University of Manitoba in Winnipeg, has written a book that might as well be called *Gaia: The Living Earth from Space*. His immensely learned, highly accessible narrative is that of the true environmentalist. From these new books, coupled with earlier works by Lovelock himself (1979), Morrison (1999), Volk (1998), Westbroek (1991), and Bunyard (1996), enough responsible scientific literature on Gaia exists to fuel college/university-level curricula.

Other new comprehensive and comprehensible contributions to the Gaia debate include the incredibly detailed 400,000-year-old annual ice core record of climatic change and atmospheric CO_2 rise. The story of how international science obtained this fund of Pleistocene data from the central Greenland ice sheet reads like a novel (Mayewski and White, 2002). Another fascinating book, an integration of modern ecological processes and other complex systems determined by the second law of thermodynamics, is in the works for 2004 (Schneider and Sagan, forthcoming). This treatise on energy sees Gaia, even its origin over 3.5 billion years ago, as a part of the tendency of the universe to increase in complexity as energetic gradients are broken down. The sun inexorably loses its heat and light into the cold blackness of space. This temperature and other gradient imperatives generate and sustain organized systems that seem to appear from nothing. These ''other-organized'' systems, however, enhance thermodynamic, informational, pressure, and other gradient reduction. ''Nature,'' write Schneider and Sagan, ''abhors [not just a vacuum] but all gradients.'' Gaia can be understood as a peculiar, long-lived, expanding, and complexifying ''planetary-scale gradient reducer.'' The history of thermodynamics and this arcane science's ability to describe all manner of energy flow phenomena sheds light on the intimate connection between the physical-chemical sciences and the evolution of life. Furthermore, since the 1970s Gaia theory has continued to draw attention to the mighty microbe, the diverse set of bacterial cells, their communities, and their larger protoctist descendants (Margolis, McKhann, and Olendzenski, 1992). How microbes metabolize and organize into effective, functional communities forms a crucial component of Gaian research.

Gaia theory's original postulates were limited to global temperature, acidity-alkalinity, and the composition of reactive gases of the air. The new Gaia, whatever her name, becomes respectable because postulated explanations for Earth's surface activity require living beings and interrelations between them and the rest of the lithosphere.

Here are just a few scientific queries stimulated by the wily ways of the ancient Earth goddess in elegant modern dress. Without inquisitive prodding, as Jim Lovelock has noted, such questions of the coy Gaian goddess would never have been raised by polite scientific society.

1. Are plate tectonics (i.e., the deep, lateral movements of the lithosphere apparently limited in the solar system to the Earth) a Gaian phenomenon?

2. Is the remarkable abundance of aluminosilicate-rich granite, a crustal rock type unknown elsewhere in the solar system and one that comprises 0.1 percent of the Earth's volume, directly related to the presence of life? Did water flow and oxygen release, so strongly influenced by life over 3 billion years, generate the granitic raised portions of the plates?

3. Is the Earth's distribution of certain metals and other elements, those known to strongly interact with life (e.g., phosphorus, phosphorites, banded iron formation, marine and freshwater iron-manganese nodules), a Gaian phenomenon? Are Archean conglomeratic, organic-rich sedimentary gold deposits related to life?

4. Is the rate of dissolution of vast quantities of salt (sodium chloride) retarded by biological activity (e.g., in the M-layer beneath the Mediterranean sea, the Hormuz basin of Iran, the Texas Permian Basin deposits, and the great German and North Sea Permian zechstein deposits)? In other words, are the worldwide evaporite deposit patterns a Gaian phenomenon?

5. Can long-lasting thermodynamic disequilibria and reactive gaseous chemical anomalies in a planetary atmosphere be taken as a presumptive sign of life?

6. If life is primarily responsible for the enormous differences in the meters (m) of precipitable water on the surfaces of the three silica-rich inner planets (Venus, 0.01 m; Earth, 3000 m; Mars, 0.0001 m), what have been the biological modes of water retention on Earth since the Archean eon?

7. If Earth's surface temperature has been modulated mainly by carbon dioxide, other carbonates, and organic compounds being removed from the atmosphere into limestone, to what extent have chemoautotrophic, anoxygenic phototrophic, and other metabolic pathways of CO_2 reduction supplemented the oxygenic photoautotrophy of cyanobacteria, algae, and plants?

8. Can environmental regulation studies be valid and representational in "mini-Gaia" contained systems that are closed to matter but open to sunlight or other electromagnetic energy fluxes?

No doubt many more such questions might be raised. Indeed, they are raised in several contributions to this book. Let it suffice here for me to claim that the heuristic value of this global concept is unprecedented in modern times. All of us as readers and contributors to *Scientists on Gaia: The Next Century* are profoundly indebted to Jim Lovelock for his intellectual leadership and healthy disdain of "academic apartheid." We cannot be fooled: Gaia's core identity and liveliness will survive her many fancy guises, bold dance steps, cruel deceptions, and name changes. Our Earth by any other name will smell and look and feel as sweet.

References

Arthus-Bertrand, Y. 1999. *Earth from Above*. Harry N. Abrams, New York.

Bunyard, P., ed. 1996. *Gaia in Action: Science of the Living Earth*. Floris Books, Edinburgh.

Kirchner, J. W. 2002. The Gaia Hypothesis: Fact, theory, and wishful thinking. *Climatic Change*, 52, 391–408.

Lapo, A. 1987. *Traces of Bygone Biospheres*. Mir Publishers, Moscow.

Lovelock, J. E. 1965. A physical basis for life detection experiments. *Nature* 207:568–570.

Lovelock, J. E. 1979. *Gaia: A New Look at the Life on Earth*. Oxford University Press, New York.

Lovelock, J. E. 1988. *The Ages of Gaia*. W. W. Norton, New York.

Lovelock, J. E. 2002. Reflections on Gaia. Introduction to the present volume.

Lowman, P. 2002. *Exploring Space, Exploring Earth: New Understanding of the Earth from Space Research*. Cambridge University Press, Cambridge.

Margulis, L., H. I. McKhann, and L. Olendzenski. 1992. *Illustrated Glossary of Protoctista.* Jones and Bartlett, Boston.

Margulis, L., and D. Sagan. 2002. *Acquiring Genomes: A Theory of the Origins of Species*. Basic Books, New York.

Mayewski, P., and F. White. 2002. *The Ice Chronicles; The Quest to Understand Global Climate Change*. University of New England Press, Hanover, NH.

Morrison, R. 1999. *The Spirit in the Gene: Humanity's Proud Illusion and the Laws of Nature*. Cornell University Press, Ithaca, NY.

Sagan, D. 1990. *Biospheres: Metamorphosis of Planet Earth*. McGraw-Hill, New York.

Schneider, E. R., and D. Sagan. Forthcoming. *Energy Flow: Thermodynamics and the Purpose of Life*. University of Chicago Press, Chicago, IL.

Schneider, S. H., and P. Boston, eds. 1991. *Scientists on Gaia*. MIT Press, Cambridge, MA.

Skoyles, J., and D. Sagan. 2002. *Up from Dragons: On the Evolution of Human Intelligence*. McGraw-Hill, New York.

Smil, V. 2002. *The Earth's Biosphere: Evolution, Dynamics and Change*. MIT Press, Cambridge, MA.

Sonea, S., and L. Mathieu. 2000. *Prokaryotology: A Coherent View*. University of Montreal Press, Montreal.

Thomashow, M. 1996. *Ecological Identity: Becoming a Reflective Environmentalist*. MIT Press, Cambridge, MA.

Volk, T. 1998. *Gaia's Body: Toward a Physiology of Earth*. Springer-Verlag, New York.

Westbroek, P. 1991. *Life as a Geological Force*. W. W. Norton, New York.

White, F. 1998. *The Overview Effect: Space Exploration and Human Evolution*, 2nd ed., American Institute of Aeronautics and Astronautics, Reston, VA.