CYBERNETIC COUNTERCULTURES INTENSIVE

Week 7. Planetary Cognition: Lovelock and Margulis

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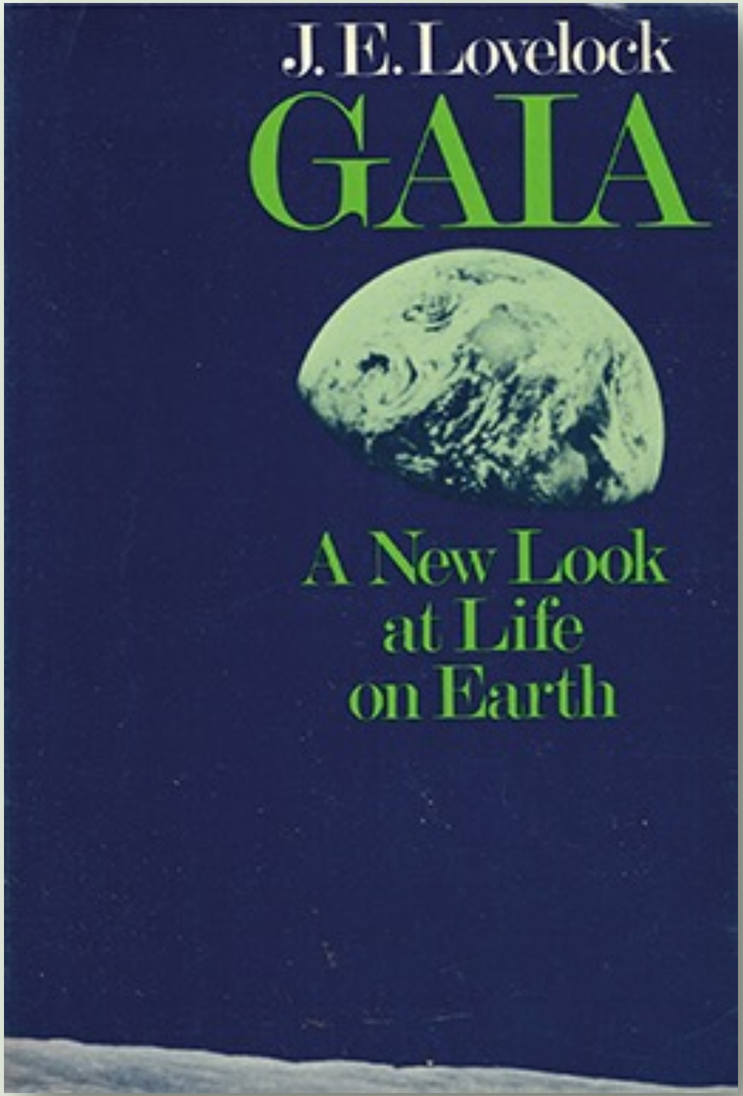
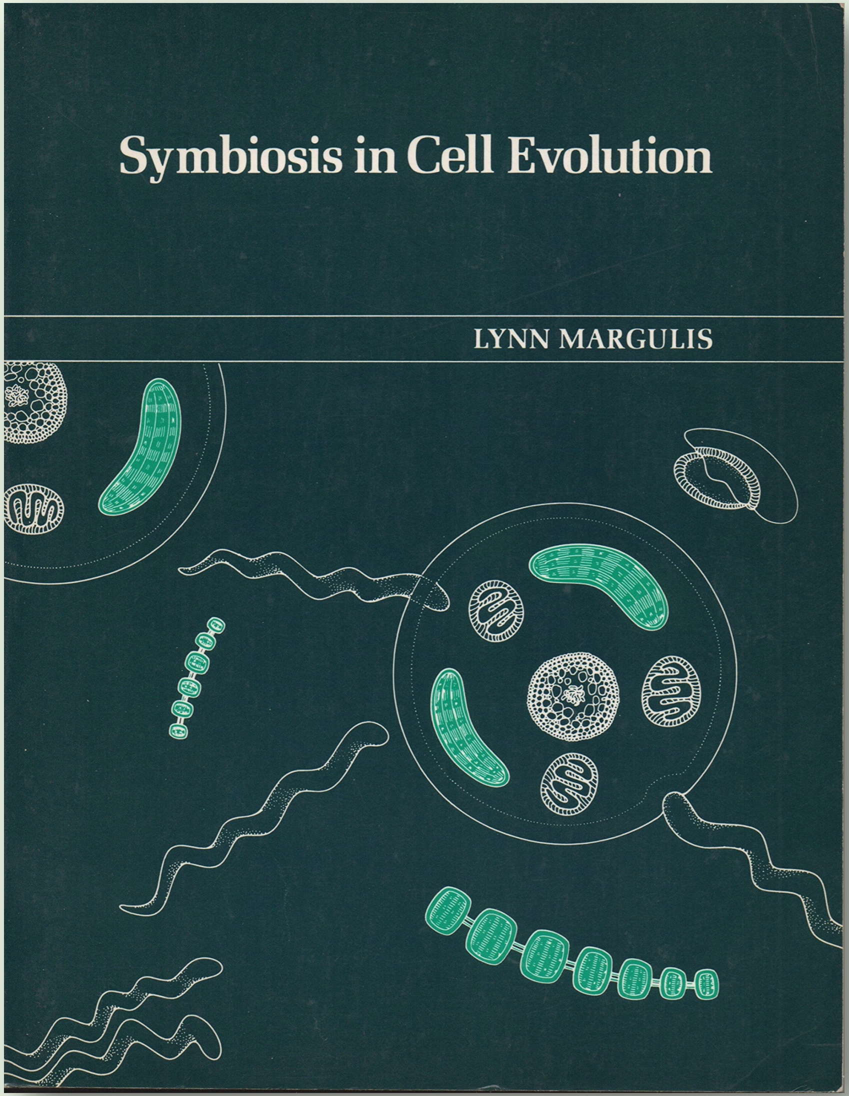
Whole Earth Rising: The Early Days of the Gaia Hypothesis

"The meeting of Lovelock, starting with the present atmosphere, with Margulis, starting from the smallest and oldest creatures, is one of the most interesting collaborations in the history of science." —Bruno Latour



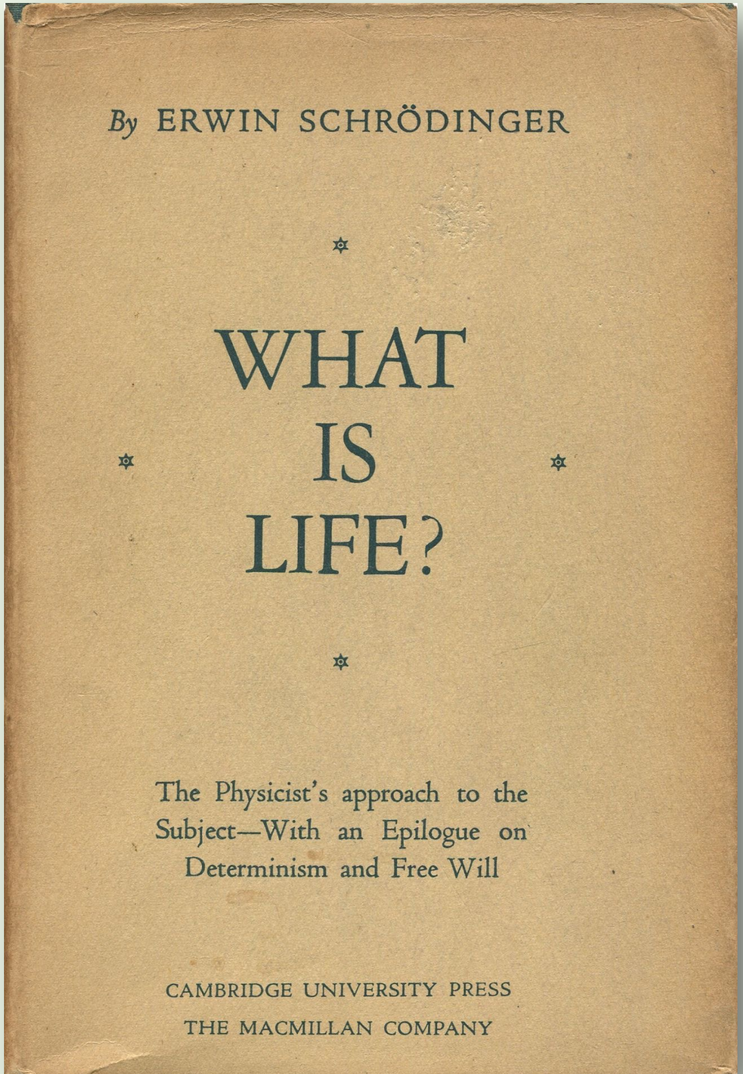


James Lovelock

—from Lynn Margulis and James Lovelock, "The Atmosphere as Circulatory System of the Biosphere: The Gaia Hypothesis," *CoEvolution Quarterly* 6 (Summer 1975).

James Lovelock (1919-2022)

The first author of the Gaia hypothesis, the British scientist began his professional career in the 1940s. Trained in chemistry, biomedicine, and engineering, Lovelock's planetary science was cultivated in the early alliance of cybernetics and information theory. His systems thinking was formed in the first wave of cybernetic concepts—negative feedback, self-regulation, self-organization —in close connection with discourses of energy and entropy in thermodynamics and their uptake in information theory to yield physical definitions of living systems.



The physicist Erwin Schrödinger's seminal text of 1944, *What is Life?*, was instrumental in forming Lovelock's conception of a living planet as a thermodynamic system operating far from equilibrium to maintain a negentropic state. On the organic front, his conception of the Gaian system was informed by the cybernetic appropriation of the physiological concept of homeostasis, as presented in the earliest Gaia papers such as "Atmospheric Homeostasis by and for the Biosphere." Lovelock would eventually propose the neologism *geophysiology* as an acceptable way to mainstream or demythologize the content of Gaian science. It did not catch on.

James Lovelock's
electron capture detector

Lovelock quit his professional position as a salaried researcher at the UK's National Institute for Medical Research in 1964 and, after numerous contributions in analytical chemistry, gas chromatography, cryobiology, and cell biochemistry, established himself as a scientific entrepreneur, consulting for private corporations such as Shell and Hewlett Packard, and scientific institutions such as NASA's Jet Propulsion Laboratory and the US National Oceanic and Atmospheric Administration. Thanks to one of his many inventions, the electron capture detector (ECD), he made the first measurements of the chlorofluorocarbons (CFCs) later determined to be responsible for the depletion of ozone in the stratosphere.

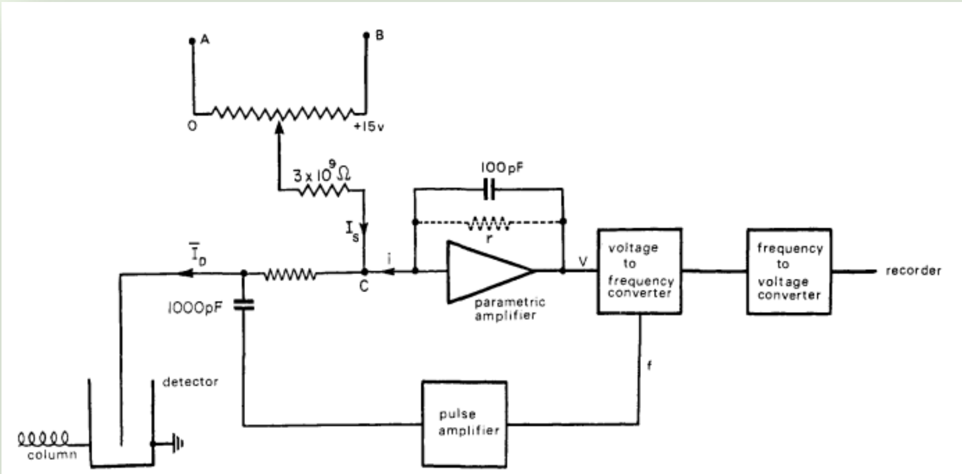


Figure 2. Circuitry for a frequency modulated Electron Capture Detector

Feedback circuitry in Lovelock's electron capture detector

Lovelock and daughter taking air samples in County Cork, Ireland.

Invented in 1957, Lovelock's electron capture detector enabled a thousand-fold increase in the sensitivity of measurements of chemicals ambient in the atmosphere. Along with his unique expertise in gas chromatography, this invention earned him an international reputation. So, the scientific specialization that especially primed Lovelock for the "discovery" of Gaia was *atmospheric chemistry*. His key innovation was then to place his advanced measurements and observations of the atmosphere into cybernetic context.

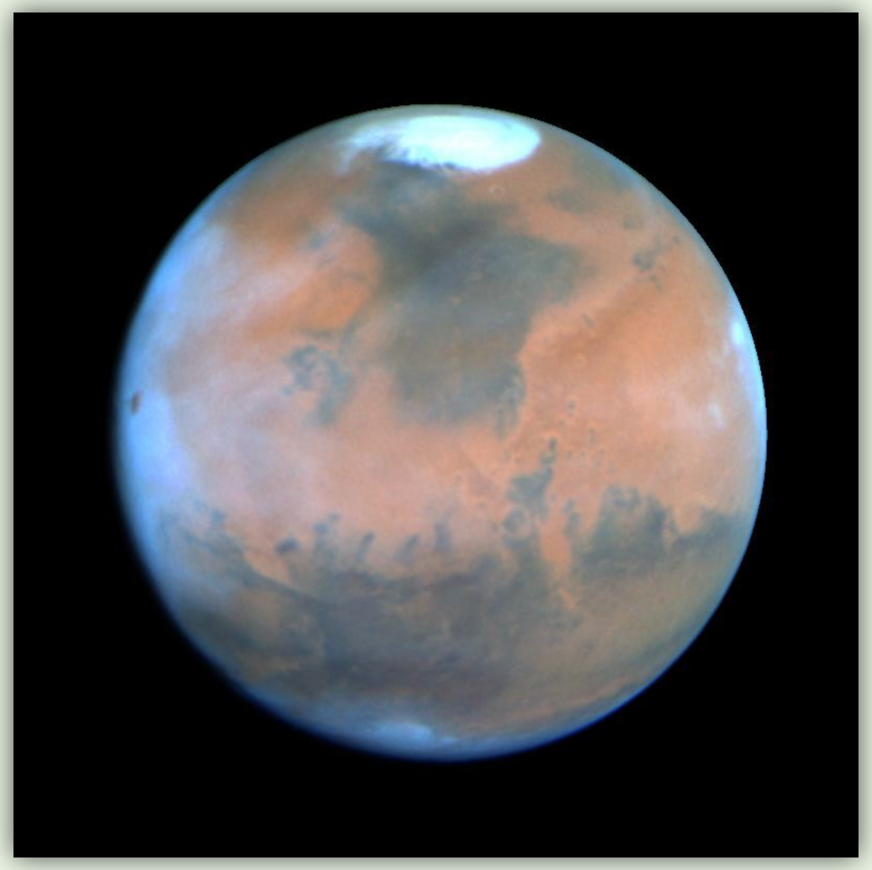
—from Lovelock’s autobiography, *Homage to Gaia* (Oxford, 2000):

“If the air is burning [that is, if its oxygen is constantly being oxidized and so pulled out of the air], what sustains it at a constant composition? . . . It came to me suddenly, just like a flash of enlightenment, that to persist and keep stable, something must be regulating the atmosphere and so keeping it at its constant composition. Moreover, if most of the gases came from living organisms, then life at the surface must be doing the regulation.

“It dawned on me [@ 1965] that somehow life was regulating climate as well as chemistry. Suddenly the image of the Earth as a living organism able to regulate its temperature and chemistry at a comfortable steady state [that is, to achieve homeostasis] emerged in my mind. At such moments, there is not time or place for such niceties as the qualification ‘of course it is not alive—it merely behaves as if it were.’”

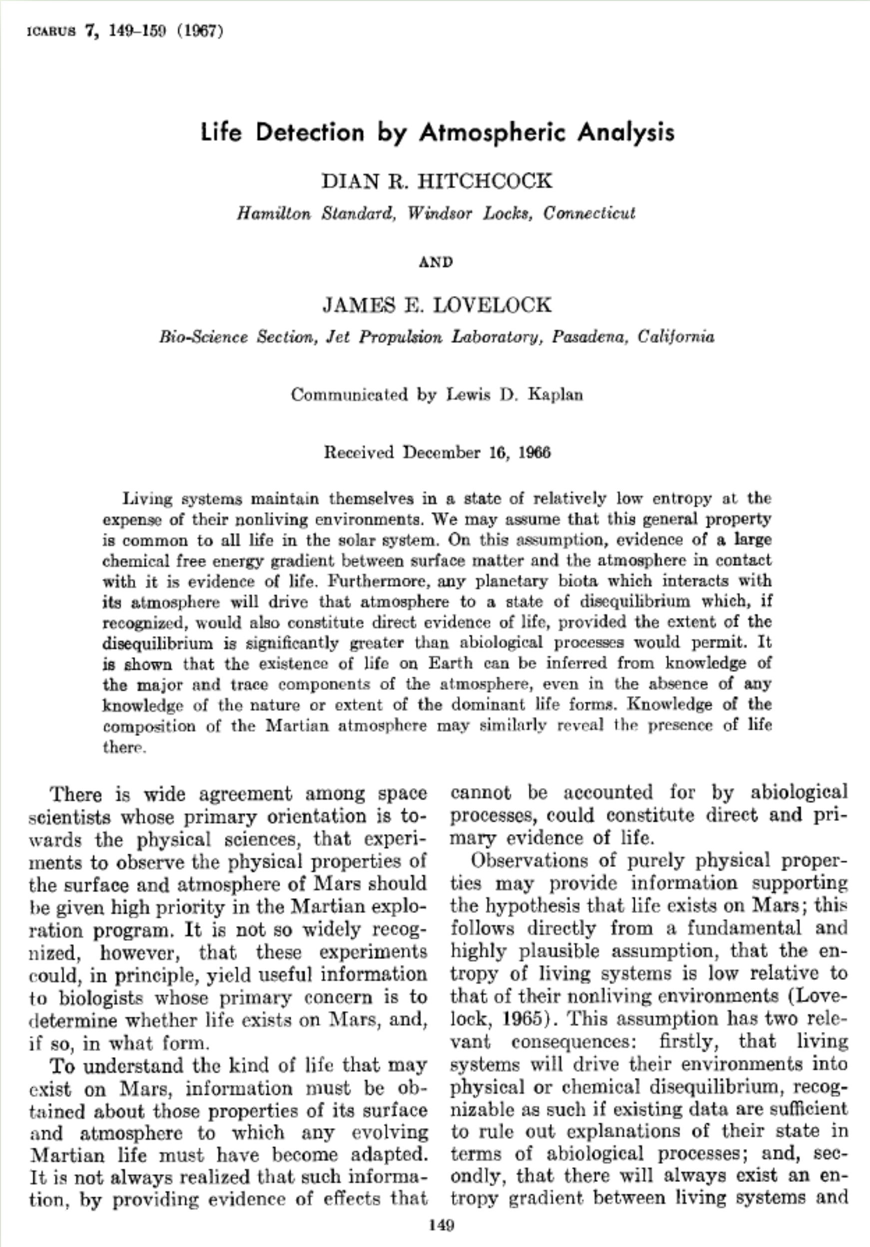
—The first stirrings of the Gaia hypothesis occurred to Lovelock as he was on contract at the Jet Propulsion Lab designing life-detection equipment for Mars landers. His Eureka moment soon guided him to the conviction that simply by Earth-based spectrographic analysis of alien atmospheres, one could do life-detection from afar (no lander necessary). NASA dismissed his opinion on that score. He recalled:

> At this time scientists still seemed to think that life flourished on Mars. I recall Carl Sagan enthusing over the wave of darkness that crosses Mars when winter ends. He and many others saw this phenomenon as indicative of the growth of vegetation. . . . This image of Mars sustained their belief in biological life-detection techniques [needing interplanetary transport]. (Lovelock, *Homage to Gaia*)



Taken by the Wide-Field Planetary Camera 2 on the Hubble Space Telescope

nssdc.gsfc.nasa.gov/photo_gallery/photogallery-mars.html



ICARUS 7, 149–159 (1967)

Life Detection by Atmospheric Analysis

DIAN R. HITCHCOCK
Hamilton Standard, Windsor Locks, Connecticut

AND

JAMES E. LOVELOCK
Bio-Science Section, Jet Propulsion Laboratory, Pasadena, California

Communicated by Lewis D. Kaplan

Received December 16, 1966

Living systems maintain themselves in a state of relatively low entropy at the expense of their nonliving environments. We may assume that this general property is common to all life in the solar system. On this assumption, evidence of a large chemical free energy gradient between surface matter and the atmosphere in contact with it is evidence of life. Furthermore, any planetary biota which interacts with its atmosphere will drive that atmosphere to a state of disequilibrium which, if recognized, would also constitute direct evidence of life, provided the extent of the disequilibrium is significantly greater than abiological processes would permit. It is shown that the existence of life on Earth can be inferred from knowledge of the major and trace components of the atmosphere, even in the absence of any knowledge of the nature or extent of the dominant life forms. Knowledge of the composition of the Martian atmosphere may similarly reveal the presence of life there.

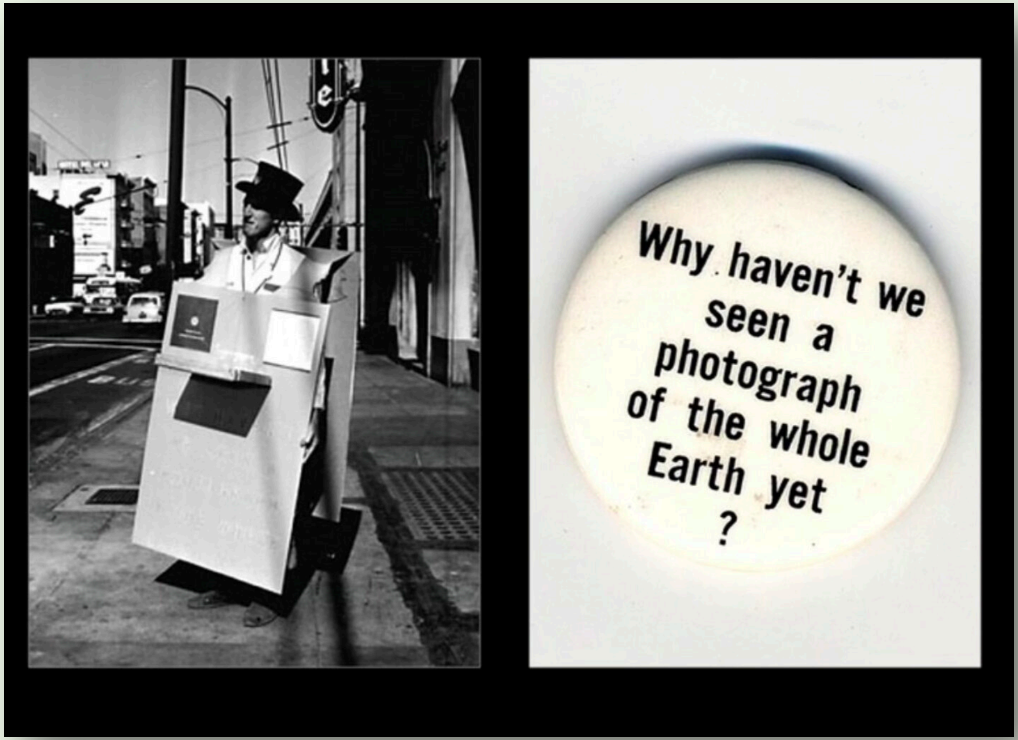
There is wide agreement among space scientists whose primary orientation is towards the physical sciences, that experiments to observe the physical properties of the surface and atmosphere of Mars should be given high priority in the Martian exploration program. It is not so widely recognized, however, that these experiments could, in principle, yield useful information to biologists whose primary concern is to determine whether life exists on Mars, and, if so, in what form.

To understand the kind of life that may exist on Mars, information must be obtained about those properties of its surface and atmosphere to which any evolving Martian life must have become adapted. It is not always realized that such information, by providing evidence of effects that cannot be accounted for by abiological processes, could constitute direct and primary evidence of life.

Observations of purely physical properties may provide information supporting the hypothesis that life exists on Mars; this follows directly from a fundamental and highly plausible assumption, that the entropy of living systems is low relative to that of their nonliving environments (Lovelock, 1965). This assumption has two relevant consequences: firstly, that living systems will drive their environments into physical or chemical disequilibrium, recognizable as such if existing data are sufficient to rule out explanations of their state in terms of abiological processes; and, secondly, that there will always exist an entropy gradient between living systems and

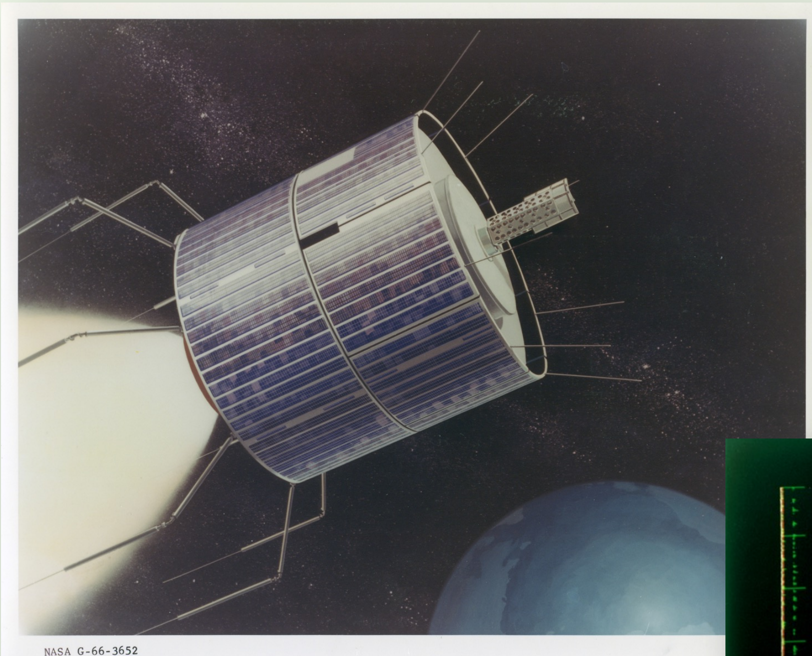
—Co-authored with JPL colleague Dian Hitchcock, the proto-Gaian paper "Life Detection by Atmospheric Analysis" is now recognized as the foundational paper on the search for alien biosignatures. Its abstract reads:

> Living systems maintain themselves in a state of relatively low entropy at the expense of their nonliving environments. We may assume that this general property is common to all life in the solar system. On this assumption, evidence of a large chemical free-energy gradient between surface matter and the atmosphere in contact with it is evidence of life. Furthermore, any planetary biota which interacts with its atmosphere will drive that atmosphere to a state of disequilibrium which, if recognized, would also constitute direct evidence of life, provided the extent of the disequilibrium is significantly greater than abiological processes would permit. . . .

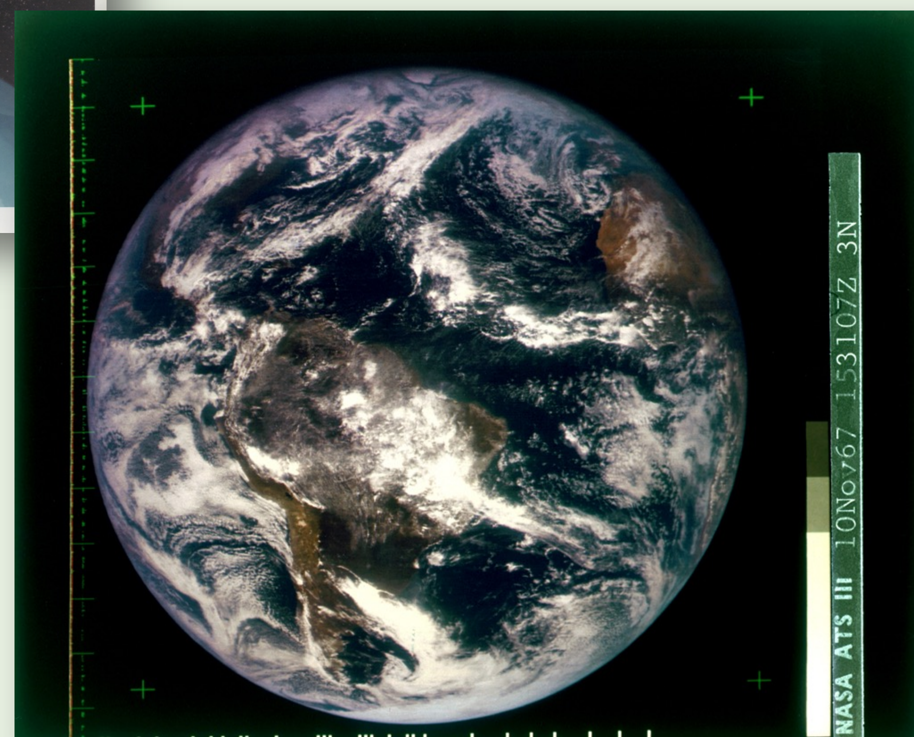


—Meanwhile, we learn: "The 'Whole Earth' of the Catalog's namesake comes from a 1966 performative project by Stewart Brand in which he campaigned for NASA to release the first satellite image of the entire Earth [as opposed to various partial views] taken from space. When the photo was released in 1967 it was used to create the Catalog's iconic cover design."

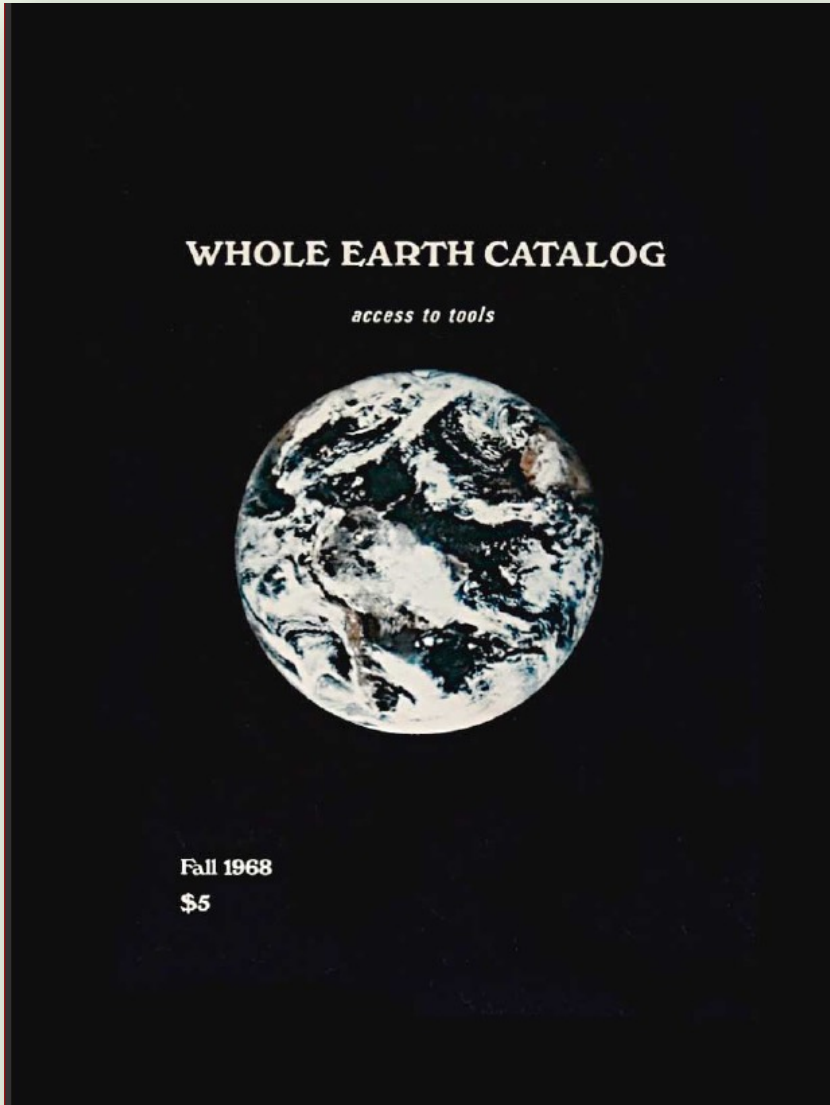
Source: https://www.praksisoslo.org/accesstotools (BC] A detailed and informative article with a critical take on Whole Earth hype.)



—But there was no conspiracy to withhold "a photograph of the whole Earth" from the public. The earliest attempts were scratchy and stitched-together b&w mosaics. Taken by a NASA ATS-III weather satellite, the first high-quality and intact whole-Earth image in color arrived on November 10, 1967.



And a year later, there it is. Transported aloft by space technology, "We are as gods and might as well get good at it."



FUNCTION

The WHOLE EARTH CATALOG functions as an evaluation and access device. With it, the user should know better what is worth getting and where and how to do the getting.

An item is listed in the CATALOG if it is deemed:

1) Useful as a tool,
2) Relevant to independent education,
3) High quality or low cost,
4) Not already common knowledge,
5) Easily available by mail.

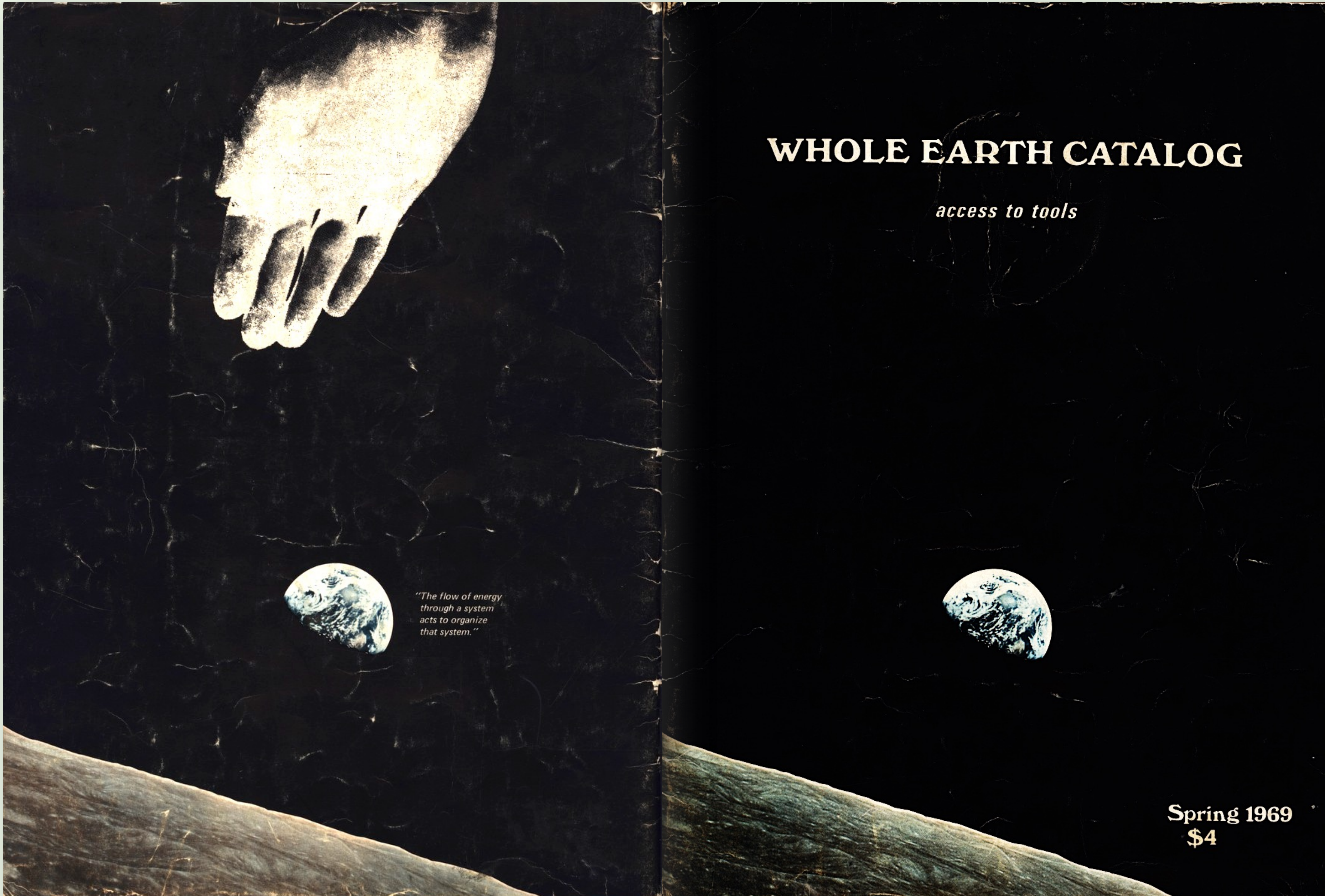
This information is continually revised according to the experience and suggestions of CATALOG users and staff.

PURPOSE

We are as gods and might as well get good at it. So far, remotely done power and glory—as via government, big business, formal education, church—has succeeded to the point where gross defects obscure actual gains. In response to this dilemma and to these gains a realm of intimate, personal power is developing—power of the individual to conduct his own education, find his own inspiration, shape his own environment, and share his adventure with whoever is interested. Tools that aid this process are sought and promoted by the WHOLE EARTH CATALOG.

Earthrise seen from Apollo 8, December 24, 1968, in its original orientation. NASA.

The hand of "Man," or the hand of God? In any event, "The flow of energy through a system acts to organize that system."



AAS 68-190

PLANETARY ATMOSPHERES: COMPOSITIONAL AND OTHER CHANGES ASSOCIATED WITH THE PRESENCE OF LIFE

James E. Lovelock and C. E. Giffin*

One achievement of the space program was that it finally succeeded in convincing the Geoplanarians that the Earth was not flat; such an enlargement of our view is not restricted to popular mythology; a new view of the Earth from space is an inevitable by-product of all explorations of the planets, whether real or in the imagination. A particular example, which is the subject of this paper, is a clearer view of the Earth's ecosystem which comes from a consideration of the chemical composition of the atmospheres of Mars, Earth and Venus.

In 1965, we were interested to know the extent to which information on the chemical composition of planetary atmospheres could constitute direct and primary evidence of life(1). In other words, could the chemical analysis of a planetary atmosphere constitute a life detection experiment. We convinced ourselves and a few others that such an experiment could indeed detect the presence of life on a planet and with a signal-to-noise ratio at least as good as that of other life detection experiments. At that time, the detection of life on Mars seemed ample justification for this exobiological exercise; as time passed, however, evidence accumulated from the Mariner missions(2) and from the infrared astronomy of the Connes and Kaplan(3) to suggest that Mars may not be far from an abiological steady state and therefore unlikely to be a base for life. At this time,

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

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James E. Lovelock and C. E. Giffin, "Planetary Atmospheres: Compositional and Other Changes Associated with the Presence of Life," *Advances in the Astronautical Sciences* 25 (1969): 179–193.

—Meanwhile, back over at NASA, the main lines of the Gaia hypothesis proper first emerged in the later 1960s, right in synch with Earthrise, with Lovelock's sketches for a concept of Earth's atmosphere as a self-regulating system. Once Lynn Margulis came on board a few years later, the purview of the theory was extended to the biosphere altogether.

The phrase "biological cybernetic system" occurs in this paper Lovelock lead-authored on behalf of NASA, delivered in 1968 at a meeting of the American Astronautical Society. Here Lovelock made the heterodox suggestion that NASA's planetary exploration program, while aimed at Mars and Venus, had in fact made a profound yet underappreciated discovery regarding a "living Earth."

Lovelock and Giffin, "Planetary Atmospheres," continued :

The planetary exploration program has already contributed in many ways to the better understanding of the Earth as a planet. If it can succeed in revealing in full detail the biological cybernetic system of the Earth's atmosphere, this would seem to be a role nearly as important as the discovery of life elsewhere. Even if the other planets, Mars and Venus, show no evidence of life, their composition and properties still represent important reference points of abiological steady state equilibria against which the living Earth can be compared.

—In Lovelock's view, this discovery was that our planet's atmosphere constitutes a system that regulates its own composition. Improbably within an otherwise abiotic cosmos, when coupled to the biota of a "living Earth," this system holds its proportions consistent over geological time in a far-from-equilibrium state, thus ensuring that the planet remains viable for life altogether. The implication will be that with the emergence of the Gaian system in the early history of life on Earth, the biota produced a kind of protective planetary membrane maintaining the conditions for their own continuation. For Lovelock, this cybernetic recognition regarding our own planet rivaled the importance of NASA's ostensible mission of searching for life on other planets.

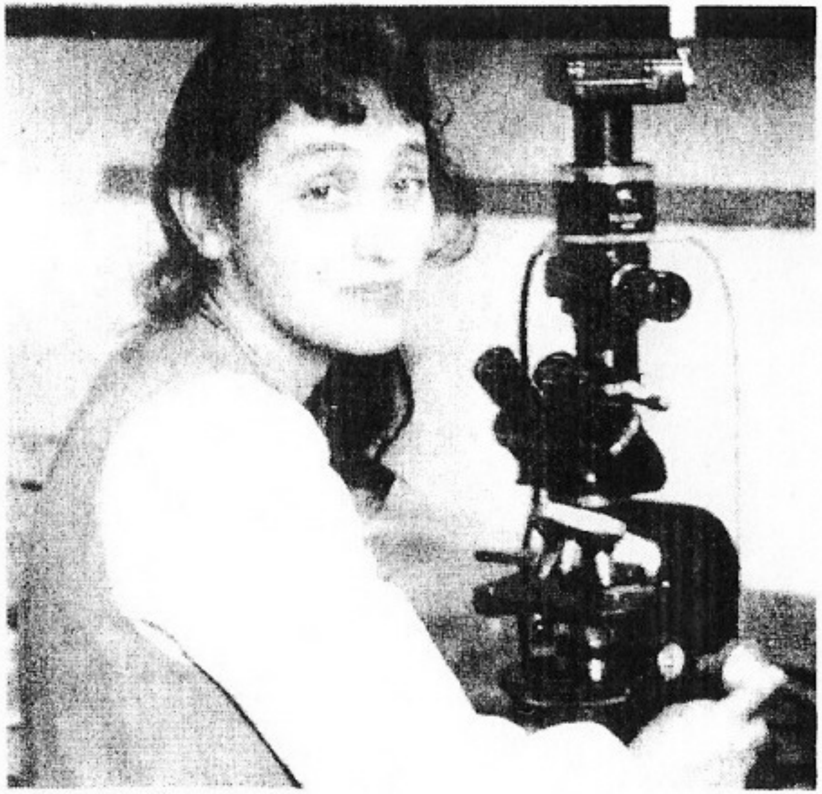
Lovelock has retold the story of the origin of "Gaia" as the name of his scientific concept on numerous occasions, regarding the time he informally informed his neighbor, the novelist William Golding, during one of their regular country walks, about his new concept of the Earth's atmosphere as a self-regulating system. But I think his most telling account is the one recorded in an interview with the Canadian science journalist David Suzuki in the nature documentary *The Sacred Balance*. In this particular conversation, Lovelock included a set of details that usually went unmentioned:

"William Golding said, 'If you're going to have a big idea like that you'd better give it a proper name.' So I said, 'Good, what would you call it?' He said, 'I'd call it Gaia.' . . . And we went on walking for twenty minutes, talking at complete cross-purposes, because I didn't have a classical education. I didn't know anything about Gaia, the Greek goddess. But I did know about g-y-r-e, gyre, the great whirl in the ocean or in the atmosphere, and this made sense of course, this was a fed-back system, and this is what he's talking about. And he said, 'No no no no no, I mean the Greek goddess of the Earth.' And then it clicked, of course. . . ."

—from David Suzuki, *The Sacred Balance*, Part 1, "Journey into New Worlds"

—The larger story around Golding's fabled suggestion tells us that, when the name of Gaia was first proposed, Lovelock had no idea what his friend was talking about! Instead, latching onto the homonym made available in British pronunciation, Lovelock immediately jumped to a cybernetic construction: "gyre, the great whirl in the ocean or in the atmosphere . . . a fed-back system." Possession of these finer details may detain one from being led too far astray by the mythological glamor of the chthonic figure named Gaia. For despite all the conjectures and free associations that have been spent on the matter, the Gaia hypothesis, at least in its initial conception, simply had nothing to do with the mythological Gaia. I share the conviction also expressed by Lynn Margulis that altogether too much has been made of the *name* of Gaia as opposed to the content of its theory. This nominal misreading is understandable, however, in the absence of the information needed to bring out the cybernetic conceptuality that name succeeded in obscuring.

Lynn Margulis



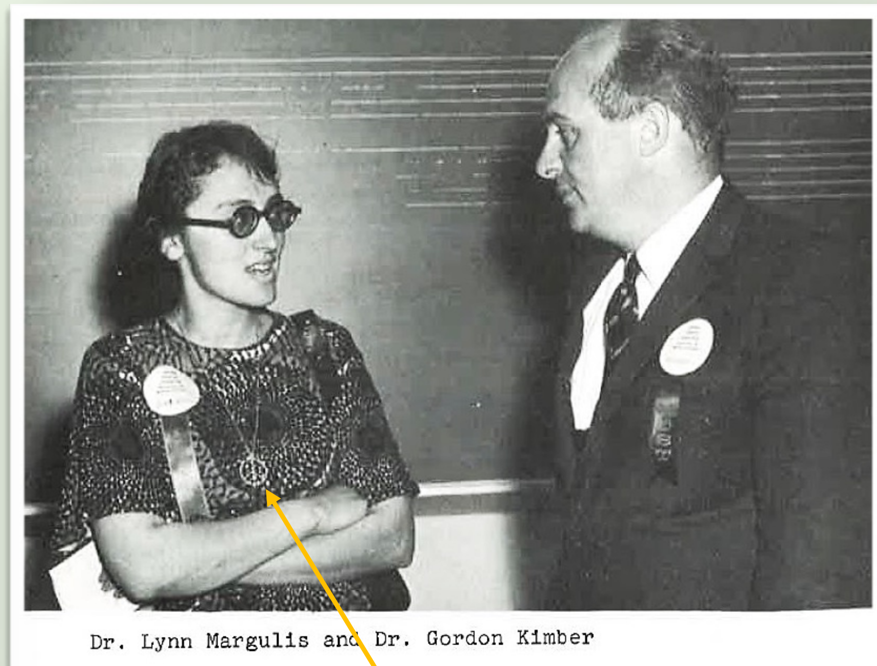
Lynn Margulis

—from Lynn Margulis and James Lovelock, "The Atmosphere as Circulatory System of the Biosphere: The Gaia Hypothesis," *CoEvolution Quarterly* 6 (Summer 1975).

—One generation younger than Lovelock, Lynn Margulis (1938-2011) began her academic career in the 1960s. Margulis's specialized training was in genetics and cellular systems. Her signature innovation, serial endosymbiosis theory (SET), first published in 1967, regarding the origin of the eukaryotic cell from stepwise mergers among pre-evolved bacterial precursors, ranged far beyond the accounts of microbial evolution then current. Not long after these precocious maverick contributions, Margulis absorbed Lovelock's lessons on thermodynamics and classical cybernetics as foundations for the Gaia concept, ways of thinking that took her ever further away from mainstream biological thinking.

1957: Lynn Alexander marries Carl Sagan upon graduation from the University of Chicago's undergraduate program at the age of 19. They divorce in 1964.

1970: That spring, Lynn Margulis, on the tenure track at Boston University, gives an invited talk on "Cytoplasmic Genes: Our Precambrian Legacy" at the Stadler Genetics Symposium at the University of Missouri.



Dr. Lynn Margulis and Dr. Gordon Kimber

Peace Sign

J. Theoret. Biol. (1967) **14**, 225–274

On the Origin of Mitosing Cells

LYNN SAGAN

Department of Biology, Boston University
Boston, Massachusetts, U.S.A.

(*Received* 8 *June* 1966)

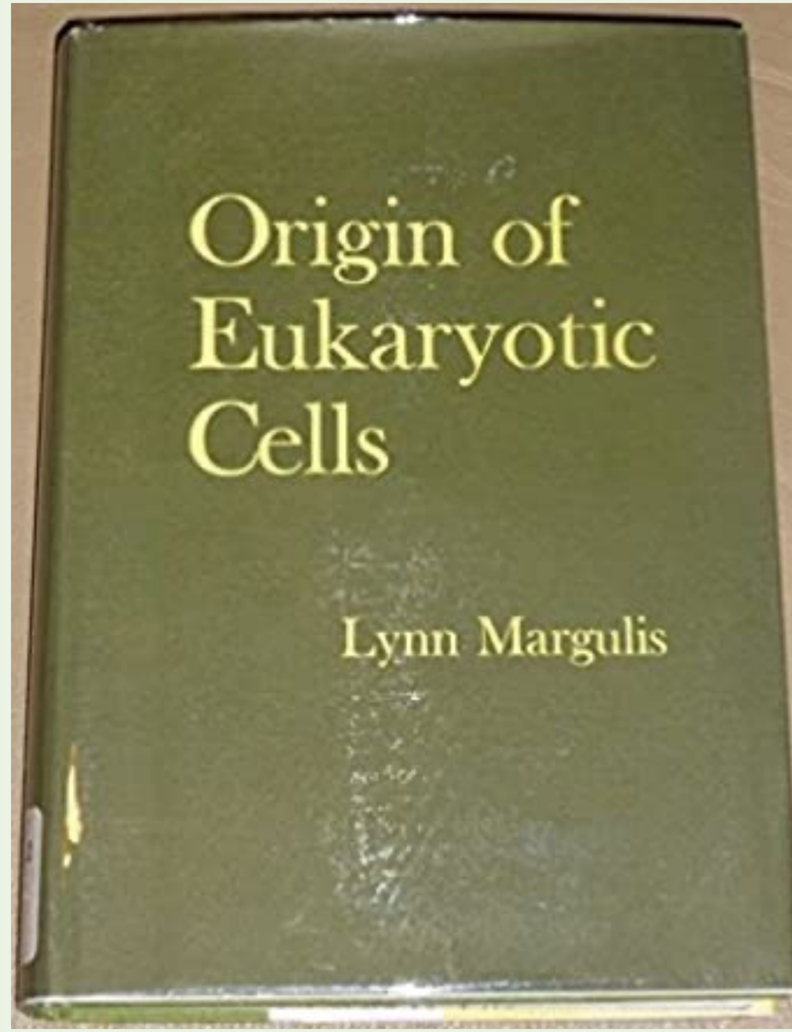
A theory of the origin of eukaryotic cells ("higher" cells which divide by classical mitosis) is presented. By hypothesis, three fundamental organelles: the mitochondria, the photosynthetic plastids and the (9+2) basal bodies of flagella were themselves once free-living (prokaryotic) cells. The evolution of photosynthesis under the anaerobic conditions of the early atmosphere to form anaerobic bacteria, photosynthetic bacteria and eventually blue-green algae (and protoplastids) is described. The subsequent evolution of aerobic metabolism in prokaryotes to form aerobic bacteria (protoflagella and protomitochondria) presumably occurred during the transition to the oxidizing atmosphere. Classical mitosis evolved in protozoan-type cells millions of years after the evolution of photosynthesis. A plausible scheme for the origin of classical mitosis in primitive amoeboflagellates is presented. During the course of the evolution of mitosis, photosynthetic plastids (themselves derived from prokaryotes) were symbiotically acquired by some of these protozoans to form the eukaryotic algae and the green plants.

The cytological, biochemical and paleontological evidence for this theory is presented, along with suggestions for further possible experimental verification. The implications of this scheme for the systematics of the lower organisms is discussed.

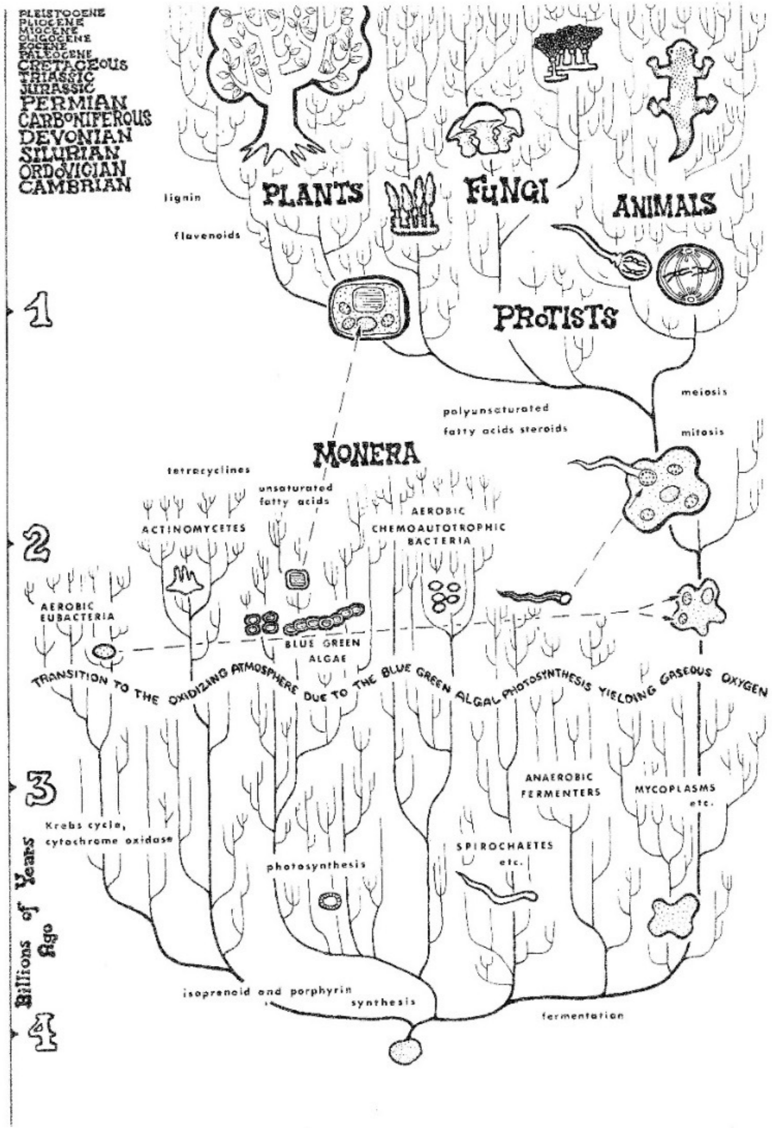
1. Introduction

All free-living organisms are cells or are made of cells. There are two basic cell types: *prokaryotic* and *eukaryotic*. Prokaryotic cells include the eubacteria, the blue-green algae, the gliding bacteria, the budding bacteria, the pleuropneumonia-like organisms, the spirochaetes and rickettsias, etc. Eukaryotic cells, of course, are the familiar components of plants and animals, molds and protozoans, and all other "higher" organisms. They contain subcellular organelles such as mitochondria and membrane-bounded nuclei and have many other features in common.

"The numerous and fundamental differences between the eukaryotic and prokaryotic cell which have been described in this chapter have been fully recognized only in the past few years. In fact, this basic divergence in cellular structure which separates the bacteria and blue-green algae



Yale University Press, 1970



Frontispiece: Theory of the origin and evolution of eukaryotic cells

Origin of Eukaryotic Cells

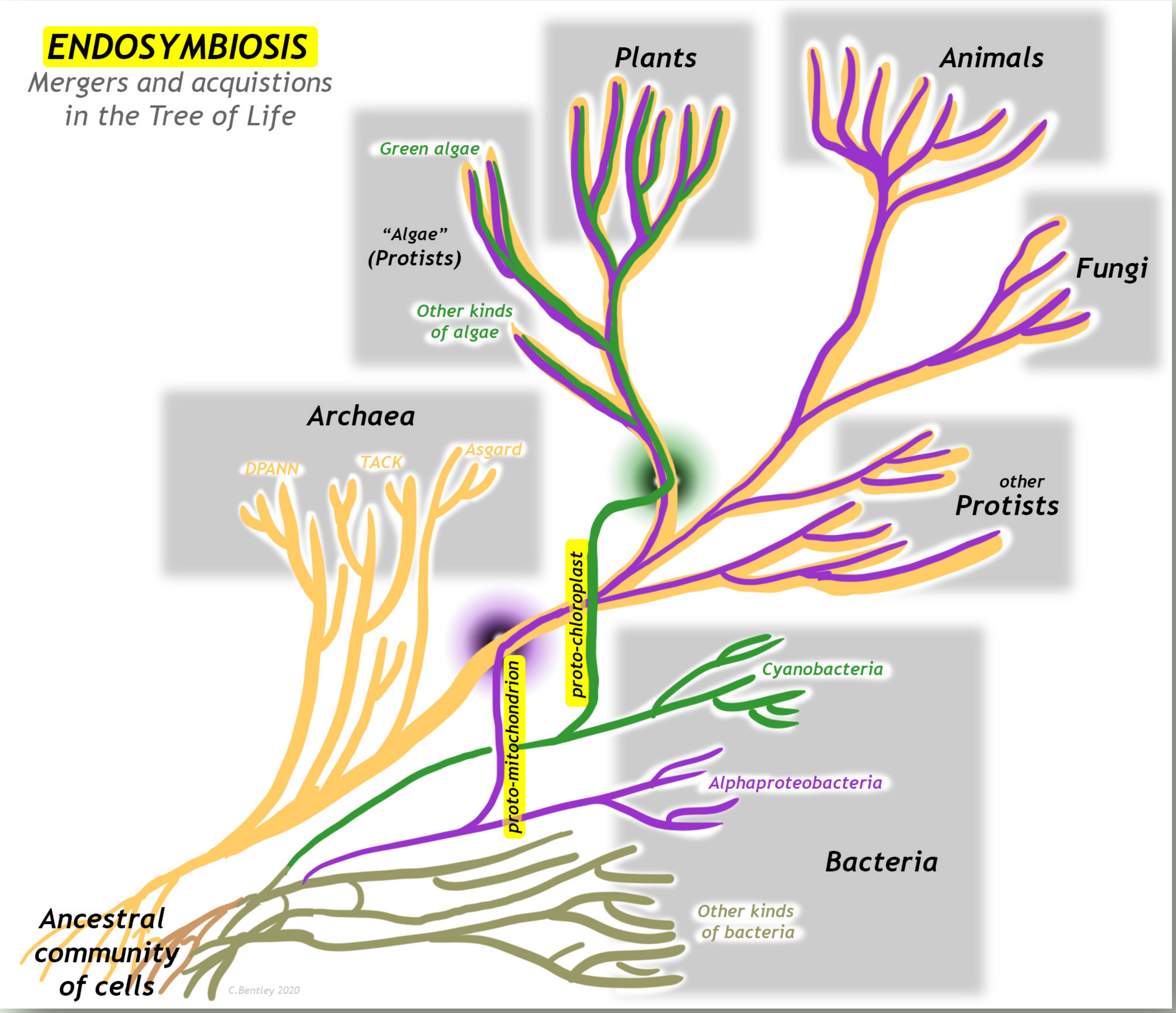
Evidence and Research Implications for
a Theory of the Origin and Evolution of
Microbial, Plant, and Animal Cells on
the Precambrian Earth

Lynn Margulis

—Margulis wrote and published this formidable volume just prior to the start of her collaboration with Lovelock on the Gaia concept. Its frontispiece presents in great detail—most of which is now textbook science—the original version of SET. Along the vertical timeline on the left is a nearly three-billion year stretch of evolutionary time prior to the vaunted Cambrian explosion, bifurcated by a wavy line of text that reads “transition to the oxidizing atmosphere due to the blue green algal photosynthesis yielding gaseous oxygen.” This planetary transition away from the primeval anaerobic atmosphere now goes by the name of the GOE, or “great oxidation event,” dated to around 2.2 billion years ago. Note how her frontispiece, sketching a theory that takes in the entire evolutionary history of the biota altogether, could be seen as Gaian *avant la lettre*.

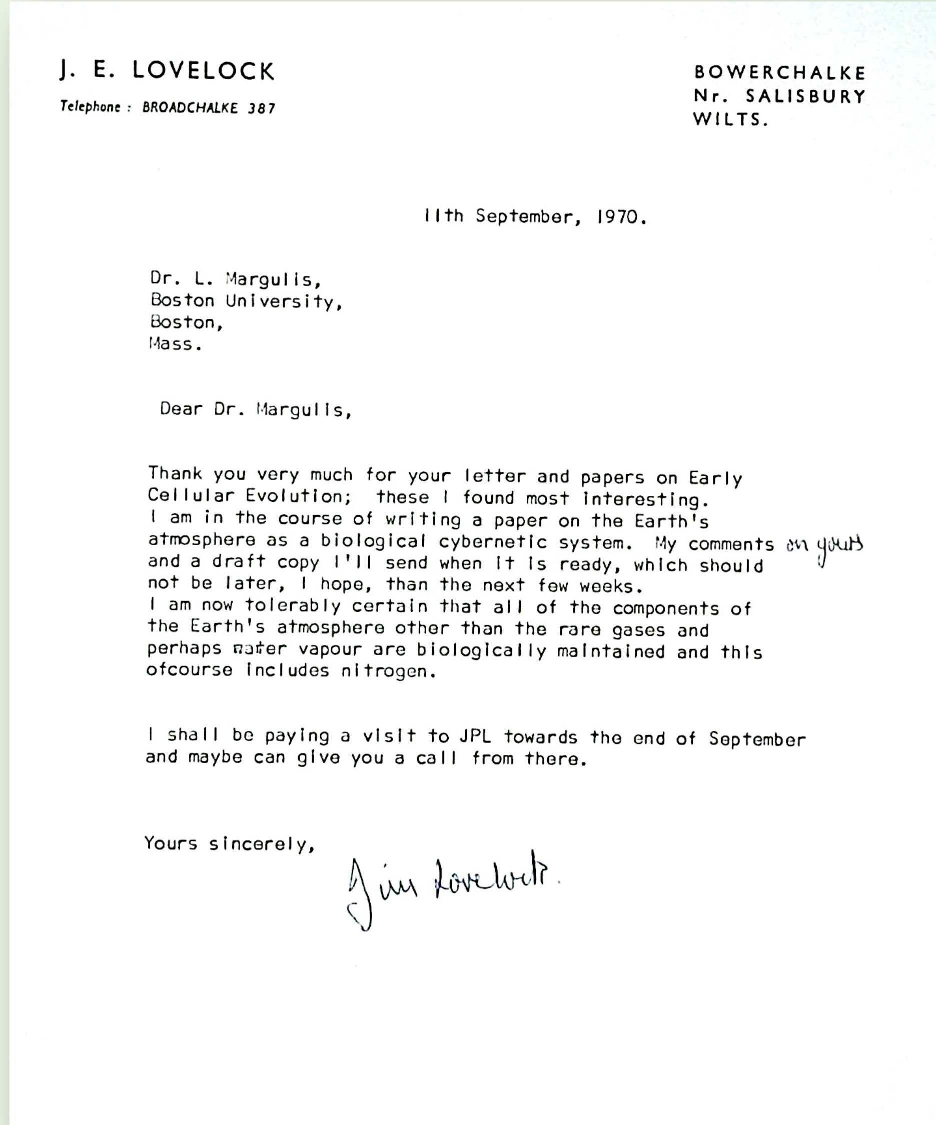
New Haven and London, Yale University Press, 1970

Here's a contemporary treatment of serial endosymbiosis theory retaining those components that have been verified by molecular sequencing.



—The advent of Lovelock's collaboration with Margulis further confirms the cybernetic inspiration of the Gaia hypothesis. In the summer of 1970, on Carl Sagan's advice, Margulis wrote to request Lovelock's thoughts as an atmospheric chemist regarding the biogenic components of the Earth's atmosphere. This communication initiated their Gaia collaboration as well as a lifelong friendship and correspondence. Lovelock's initial reply to Margulis was curt but cordial and informative. It contained two crucial and interlinked statements. First, directly documenting the tenor of his current systems thinking, Lovelock informed her, "I am in the course of writing a paper on the Earth's atmosphere as a biological cybernetic system."

One can imagine Margulis at that moment thinking to herself, "what does that mean?" Lovelock's second key statement in his initial letter to her may be read as an explanation of the first: "I am now tolerably certain that all of the components of the Earth's atmosphere other than the rare gases and perhaps water vapor are biologically maintained."


J. E. LOVELOCK
Telephone : BROADCHALKE 387

BOWERCHALKE
Nr. SALISBURY
WILTS.

11th September, 1970.

Dr. L. Margulis,
Boston University,
Boston,
Mass.

Dear Dr. Margulis,

Thank you very much for your letter and papers on Early Cellular Evolution; these I found most interesting.
I am in the course of writing a paper on the Earth's atmosphere as a biological cybernetic system. My comments on yours and a draft copy I'll send when it is ready, which should not be later, I hope, than the next few weeks.
I am now tolerably certain that all of the components of the Earth's atmosphere other than the rare gases and perhaps water vapour are biologically maintained and this ofcourse includes nitrogen.

I shall be paying a visit to JPL towards the end of September and maybe can give you a call from there.

Yours sincerely,

Jim Lovelock.

—This scientific thesis fills in the significance of describing the atmosphere as a *cybernetic* system and not just, as in the standard account at that time, as a physical or geological entity. For the cybernetic conception delivers an enhanced, *systemic* view of the biological contribution, or again, it offers a way to frame the idea of a planetary physiology that exhibits a mode of atmospheric homeostasis. That is, in Lovelock's incipient Gaian view, living systems not only *produce* the bulk of the contemporary atmosphere's chemical constituents—an idea that was already gaining ground in the geological thinking of that moment. Moreover, living systems—the planetary contributions of the microbes in particular—are also gathered into a superordinate system that *maintains* those constituents over geological time in relatively stable proportions—a completely heterodox notion that in later decades has become normal science. The hypothesis regarding a biological cybernetic system that maintains this regulatory regime would then, after intensive discussions with Margulis, go public late in 1972 under the name of Gaia.

Sidenote. Later on, Margulis would take the lead on a conception of "Water Gaia," advancing arguments to consider that Earth has retained its water (in all its forms, vaporous and otherwise) *because* it has maintained its biota, or in short, thanks to Gaia. For more, see here.

Atmospheric Environment Pergamon Press 1972. Vol. 6, pp. 579–580. Printed in Great Britain.

LETTER TO THE EDITORS

GAIA AS SEEN THROUGH THE ATMOSPHERE

THE CLIMATE and the chemical composition of the Earth is usually said to be uniquely favourable for life; indeed, it is not commonly known how small are the changes which might render the planet unsuited for the contemporary biota. An increase in oxygen concentration to 25 per cent would so increase the probability of fires that even tropical rain forests might be in hazard. A change in atmospheric pressure of 10 per cent, assuming that the composition remained unchanged, would cause a change of 4°C in the mean surface temperature; enough to set the world on an unfavourable climatic course. These are but two examples chosen from many which might show just how well suited is the environment of Earth for life. Or, is it more probable that the biosphere interacts actively with the environment so as to hold it at an optimum of its choosing?

The purpose of this letter is to suggest that life at an early stage of its evolution acquired the capacity to control the global environment to suit its needs and that this capacity has persisted and is still in active use. In this view the sum total of species is more than just a catalogue, "The Biosphere", and like other associations in biology is an entity with properties greater than the simple sum of its parts. Such a large creature, even if only hypothetical, with the powerful capacity to homeostat the planetary environment needs a name; I am indebted to Mr. William Golding for suggesting the use of the Greek personification of mother Earth, "Gaia".

As yet there exists no formal physical statement of life from which an exclusive test could be designed to prove the presence of "Gaia" as a living entity. Fortunately such rigour is not usually expected in biology and it may be that the statistical nature of life processes would render such an approach a sterile one. At present most biologists can be convinced that a creature is alive by arguments drawn from phenomenological evidence. The persistent ability to maintain a constant temperature and a compatible chemical composition in an environment which is changing or is perturbed if shown by a biological system would usually be accepted as evidence that it was alive. Let us consider the evidence of this nature which would point to the existence of Gaia.

Here is the first published instance of "Gaia" in its scientific sense, submitted under Lovelock's name alone. But their correspondence confirms that the presentation of Gaia here is now a joint theory, worked over by both Lovelock and Margulis, regarding the biosphere altogether as a system "with the powerful capacity to homeostat the planetary environment." This phrasing represents a further refinement of Lovelock's initial insight regarding the atmosphere as a "biological cybernetic system."

—At the start of 1972, Lovelock and Margulis had met in person to sort out a working arrangement for a long-distance correspondence to develop these ideas into a full-fledged co-authored scientific paper. In their initial efforts, he brought his cybernetic schemas and observational data on the chemistry of planetary atmospheres, while she brought the finer biological details centered on cellular and microbial metabolisms. I will open up for brief inspection just one letter from this period in order to observe Margulis's testimony regarding Lovelock's implicitly cybernetic arguments. Dated January 24, 1972, this letter documents a Eureka moment of her own, from her study of "your oxygen article," a lead-authored Lovelock essay just then under submission to the journal *Atmospheric Environment*, "Oxygen in the Contemporary Atmosphere." In her letter, Margulis lets Lovelock know that his concept of a *biological* cybernetic system, built up from negative-feedback cycles regulating environmental variables, has finally clicked for her.

72.01.24-M

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January 24, 1972

Dr. James Lovelock
Bowerchalke
Salisbury, Wiltshire
ENGLAND

Dear Jim,

The mail will probably cross again. Anyway, I have read your oxygen article five times and finally not only do I dig it but I find it brilliant. Have you sent it in? Even if so, I think you should strongly consider reducing the size, outlining the argument (I'll do this if you want my collaboration) and submitting it as a technical comment to Science in response to Leigh Van Valens article. Van Valen raised this issue well but did not perceive the solution. I would also change the wording in several places to make it more transparent to the potential ecological and general biological audience. Please let me know soon what you think of this possibility.

Methane producers as far as I know are fermenting anaerobes. If the local environment gets too aerobic they turn off. Therefore they release less methane into the atmosphere. Therefore, according to you, less gets transported up to circuitously loose hydrogen (via water, according to you) and the mechanism for keeping aerobic shuts off. This provides more anerobic niches and the methane bacteria go to work again. Your basic conceptual plan here must be correct. I am confused on page 4 about lines 5,6,7, etc. from bottom.

Neither have I a casette recorder, and I'd much prefer to write than talk. However, you feel free to send casettes.

Enclosed is a revised memo which I made up about you. I hope it is reasonably accurate and that the powers in charge will take the next step.

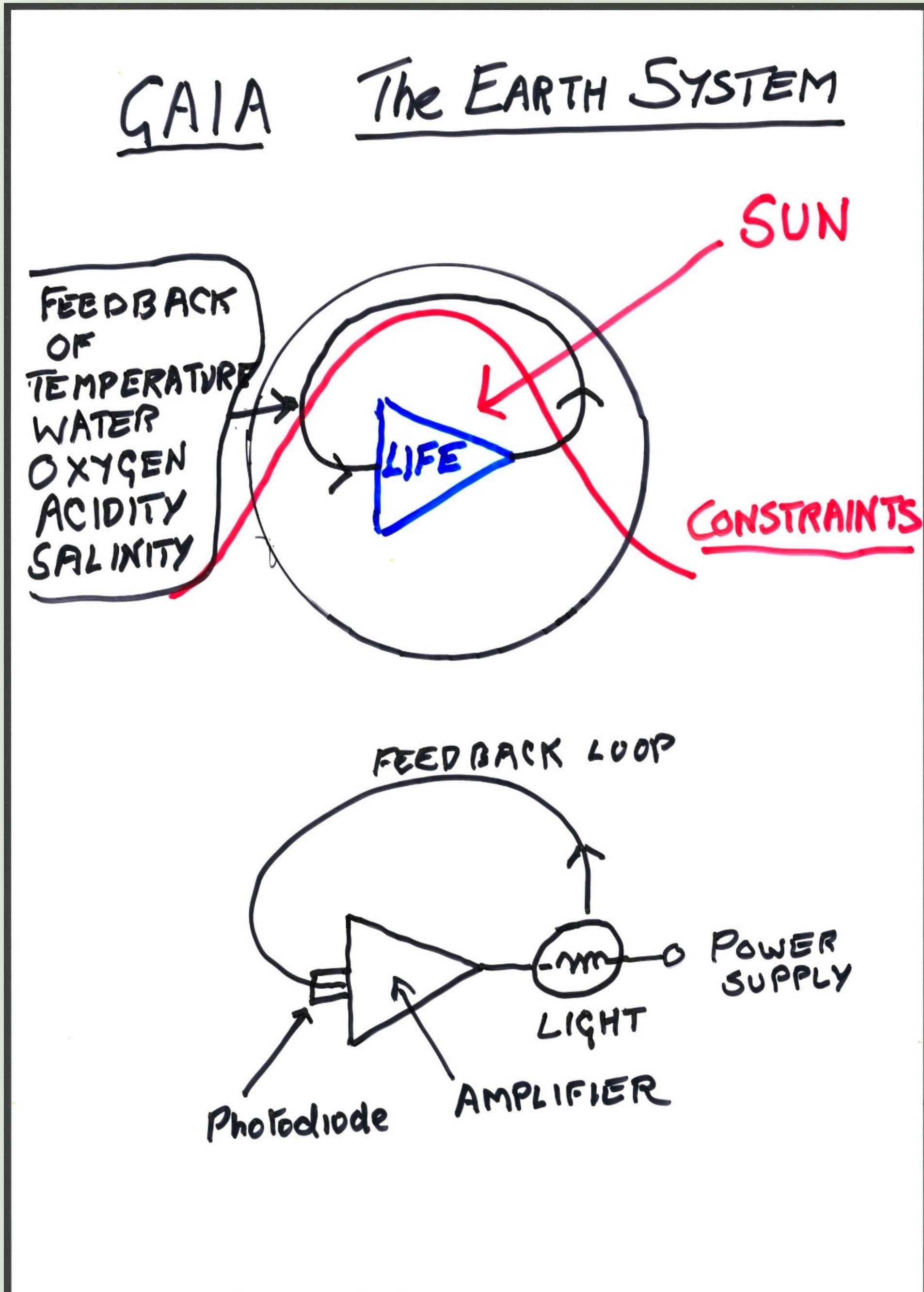
See if you can get a hold of MIT's Tech Review, latest issue. Steward Wilson is supposed to have an article on the Interactive Lecture system in it. I am also confused about the N_2 argument. Carl claims there is plenty of (undetected?) N_2 on Mars in proportion to CO_2. Although on intuitive grounds I feel you are right "that if Mars were lifeless then N_2 would be absent from its atmosphere"...I wish you'd reiterate the grounds for this, slowly. I've

Margulis to Lovelock, January 24, 1972:

". . . I have read your oxygen article [in manuscript] five times and finally not only do I dig it but I find it brilliant. . . .

"Methane producers as far as I know are fermenting anaerobes. If the local environment gets too aerobic they turn off. Therefore they release less methane into the atmosphere. Therefore, according to you, less gets transported up to circuitously loose hydrogen (via water, according to you) and the mechanism for keeping aerobic shuts off. This provides more anaerobic niches and the methane bacteria go to work again. Your basic conceptual plan here must be correct. . . ."

At this very early stage in their collaboration, Lovelock and Margulis are still teaching each other what they need to learn in order to bring their respective specializations together, hashing out the chemical and biological propositions at the base of the Gaia hypothesis. To tell from this testimony, Margulis has just now wrapped her head fully around Lovelock's cybernetic scheme, in which atmospheric self-regulation emerges from circular functions drawn from the operational closure of one of Gaia's feedback circuits, here, a component of the Gaian system in the effective form of a negative feedback loop between the anaerobic and aerobic portions of the biosphere. In this instance, methanogenic microbes are seen as successively turned on and off by their own environmental consequences, forming a biogeochemical cycle that regulates the level of atmospheric methane.



In this undated diagram, Lovelock sketches Life as the amplifier in a Gaian feedback loop. Fully identified now with the "Earth System," here is Gaia on the way to its post-countercultural career as "Earth System Science." But as we have seen, Gaia's cybernetic foundations were present from its conception:

> "There is little doubt that living things are elaborate contrivances. Life as a phenomenon might therefore be considered in the context of those applied physical sciences which grew up to explain inventions and contrivances, namely, thermodynamics, cybernetics, and information theory."

—Lovelock and Margulis, "Atmospheric Homeostasis by and for the Biosphere" (1974).

Source: Science Museum, London

After an initial round of rejections, the first coauthored Margulis and Lovelock articles on the Gaia hypothesis are published in 1974, the same year as Varela, Maturana, and Uribe's "Autopoiesis: The Organization of Living Systems." Soon enough, *CoEvolution* Quarterly came calling.

Atmospheric homeostasis by and for the biosphere: the gaia hypothesis

By JAMES E. LOVELOCK, *Bowerchalke, Nr. Salisbury, Wilts. England* and LYNN MARGULIS, *Department of Biology, Boston University, 2, Cummington Street, Boston, Mass. USA*

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ABSTRACT

During the time, 3.2×10^9 years, that life has been present on Earth, the physical and chemical conditions of most of the planetary surface have never varied from those most favourable for life. The geological record reads that liquid water was always present and that the pH was never far from neutral. During this same period, however, the Earth's radiation environment underwent large changes. As the sun moved along the course set by the main sequence of stars its output will have increased at least 30 % and possibly 100 %. It may also have fluctuated in brightness over periods of a few million years. At the same time hydrogen was escaping to space from the Earth and so causing progressive changes in the chemical environment. This in turn through atmospheric compositional changes could have affected the Earth's radiation balance. It may have been that these physical and chemical changes always by blind chance followed the path whose bounds are the conditions favouring the continued existence of life. This paper offers an alternative explanation that, early after life began it acquired control of the planetary environment and that this homeostasis by and for the biosphere has persisted ever since. Historic and contemporary evidence and arguments for this hypothesis will be presented.

It is widely believed that the abundance of the principal gases N_2 and O_2 is determined by equilibrium chemistry. One of the larger problems in the atmospheric sciences is that of reconciling this belief with the uncomfortable fact that these same gases are cycled by the Biosphere with a geometric mean residence time measured in thousands of years. The more thoroughly the inventory of an individual gas is audited the more certain it seems that inorganic equilibrium or steady state processes determine its atmospheric concentration but the same audit frequently further reveals the extent of its biological involvement. A lucid account of contemporary information on the problem of the cycle of gases is in the paper of Junge (1972).

This paper presents a new view of the atmosphere, one in which it is seen as a component part of the biosphere rather than as a mere environment for life. In this new context the incompatibilities of biological cycles and inorganic equilibria are seen as more apparent than real.

A starting point is a consideration of the profoundly anomalous composition of the Earth's atmosphere when it is compared with that of the expected atmosphere of a planet interpolated between Mars and Venus. Thus on Earth the simultaneous presence of O_2 and CH_4 at the present concentrations is a violation of the rules of equilibrium chemistry of no less than 30 orders of magnitude. Indeed so great is the disequilibrium among the gases of the Earth's atmosphere that it tends towards a combustible mixture, whereas the gases of Mars and Venus are close to chemical equilibrium and are more like combustion products.

The anomalous nature of the atmosphere has been known since Lewis & Randall (1923) first commented that at the pE and pH of the Earth the stable compound of nitrogen is the NO_3^- ion in the oceans; gaseous nitrogen should not be present. In spite of reminders by Hutchinson

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Biological Modulation of the Earth's Atmosphere

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We review the evidence that the Earth's atmosphere is regulated by life on the surface so that the probability of growth of the entire biosphere is maximized. Acidity, gas composition including oxygen level, and ambient temperature are enormously important determinants for the distribution of life. We recognize that the earth's atmosphere deviates greatly from that of the other terrestrial planets in particular with respect to acidity, composition, redox potential and temperature history as predicted from solar luminosity. These deviations from predicted steady state conditions have apparently persisted over millions of years. We explore the concept that these anomalies are evidence for a complex planet-wide homeostasis that is the product of natural selection. Possible homeostatic mechanisms that may be further investigated by both theoretical and experimental methods are suggested.

"The atmosphere, therefore, is the mysterious link that connects the animal with the vegetable, the vegetable with the animal kingdom." (Dumas and Boussingault, 1844).[1]

I. Introduction to Gaia: Le Milieu Exterior

The purpose of this paper is to develop the concept that the earth's atmosphere is actively maintained and regulated by life on the surface, that is by the biosphere. The ancient Greeks believed that all creatures on the earth, animals and plants, including man belonged to a common society. Their reference to this great communal being was "Gaia," or roughly, Mother Earth. We recognize that the earth's atmosphere differs greatly from that of the other terrestrial planets with respect to acidity, composition, redox potential, and temperature history as predicted from solar luminosity. This anomalous atmosphere has persisted over geological time periods. We believe that these properties of the terrestrial atmosphere are evidence for homeostasis on a planetary scale. In deference to the ancient Greek tradition, we refer to the controlled atmosphere-biosphere as "Gaia". We review some recent information about the terrestrial atmosphere in the light of the "Gaia hypothesis" (Lovelock, 1972; Lovelock and Margulis, 1973). First we consider the evidence that certain features of the terrestrial atmosphere (such as composition, temperature and pH) are under feedback control. We follow with suggestions for possible mechanisms involved in this complex homeostasis and ways of testing for them. We have written this paper to be comprehensible to a wide scientific audience, recognizing that an understanding of the earth's atmosphere will come only from cooperation of many scientists: planetary astronomers, geolo-

[1] See Aulie, 1970.