Week 8. Cybernetic Ecologies in *CoEvolution Quarterly*

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CYBERNETIC COUNTERCULTURES INTENSIVE

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Part Two: From Mars to Gaia to Daisy World

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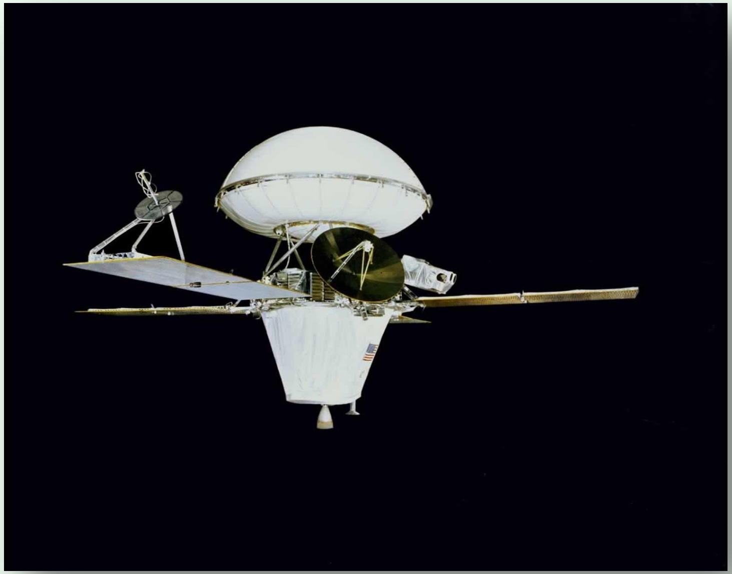
Viking spacecraft before separation of lander from orbiter



First color image of the Viking Lander 2 site

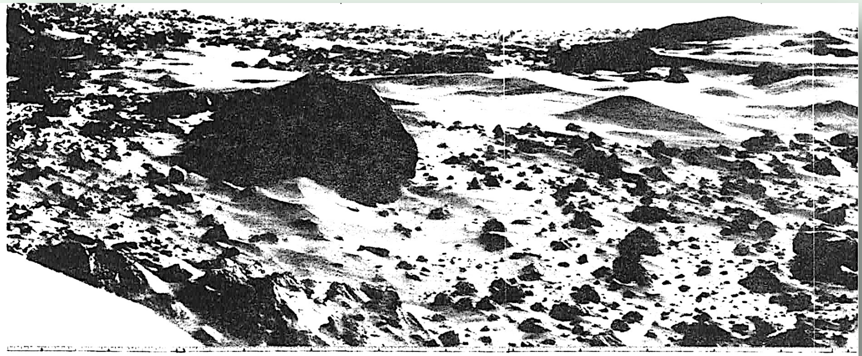
After her appearance in the Summer 1975 number of *CoEvolution Quarterly*, a year later Lynn Margulis advocates for the Gaia hypothesis again on the occasion of the successful touch-down of the Viking 2 lander on Mars on September 3, 1976. Brand reports that Lynn had "been at JPL for several days as a member of the Exobiology Subcommittee of the National Academy of Science Space Science Board, observing the quality and content of the biology going on with Viking."

Her conversation with Stewart Brand regarding the readings coming back from Viking's life-detection apparatus are an example of the *Gaian reversal*, the way that Gaia's conceptual gravity generally tends to bend one's cosmological attention back to Earth. NASA has always dangled the possibility of finding life *elsewhere*—on Mars, on Titan, on an exoplanet—as a way to maintain public support for federal funding of its space science. Thus, it created the science of *exobiology* (later rebranded *astrobiology*) despite the absence as yet of a direct object of study—alien life. Gaia theory rediscovers life on Earth.

Margulis and Lovelock both enjoyed significant NASA funding. But at the same time, their Gaia hypothesis already predicted the *absence* of life on Mars. Here Margulis explains why the *negative* if "inconclusive" (according to die-hards like Carl Sagan) results of Viking's life-detection equipment constituted a *positive* result in support of the predictive veracity of the Gaia hypothesis.

"The spectacular, baffling findings of Viking on Mars have brought Space back into the public mind for the first time since the Moon landing seven years ago. This time people are witness to science in process—complex experiments, contradictory data, conflicting interpretations. . . .

"Lynn has a special interest in Mars because she and her co-author of The Gaia Hypothesis, James Lovelock, have formally predicted that no life would be found on Mars. Their reasoning is that the Martian atmosphere is consistent with strictly chemical processes, in contrast with the Earth's atmosphere which shows chemical anomalies explainable only by the pressure of gas-producing organisms. According to the Gaia Hypothesis, the Earth's life effectively modulates the atmosphere, buffering it against major perturbances (Summer '75 CQ). . . ." —*SB*



Controversy Is Rife on Mars

INTERVIEWING CARL SAGAN AND LYNN MARGULIS

The spectacular, baffling findings of Viking on Mars have brought Space back into the public mind for the first time since the Moon landings seven years ago. This time people are witness to science in process — complex experiments, contradictory data, conflicting interpretations.

At Carl Sagan's invitation I covered the Viking I landing for CQ. (The last time I stayed up all night was my last peyote meeting years ago.) It was a psychedlic occasion once again as Mars gradually came through all that press equipment and muddle and took over. The first photo of the Martian surface, which came immediately after landing, was electrifying. You felt you could reach out and touch those rocks — how far away?

These two phone interviews were done the weekend of Sept. 3-6, 1976, just after Viking II landed successfully. The first complete set of life-detection experiments by Viking I was over and was busily being interpreted. Lynn Margulis had just returned to Boston from the Viking scene at the Jet Propulsion Laboratories (JPL) in Pasadena, California. She'd been at JPL for several days as a member of the Exobiology Subcommittee of the National Academy of Science Space Science Board, observing the quality and content of the biology going on with Viking.

Lynn has a special interest in Mars because she and her co-author of The Gaia Hypothesis, James Lovelock, have formally predicted that no life would be found on Mars. Their reasoning is that the Martian atmosphere is consistent with strictly chemical processes, in contrast with the Earth's atmosphere which shows chemical anomalies explainable only by the pressure of gas-producing organisms. According to the Gaia Hypothesis, the Earth's life effectively modulates the atmosphere, buffering it against major perturbances (Summer '75 CQ).

I talked to Carl Sagan, one of the scientists working on Viking, on the night after Viking II landed. The CQ's participation in Viking is entirely Carl's doing. We're grateful.

—SB

Stewart Brand: Hello Lynn. How are you?

Lynn Margulis: I broke my rib in California.

SB: What?

Margulis: This guy had just got a motorcycle and was riding it, so I thought I could do it too — consummate self-confidence based on nothing. So I pushed the handlebars in the wrong direction, and accelerated instead of stopped, and the whole goddamned bike landed right on my rib.

SB: Well, how's the Gaia Hypothesis, in view of Viking?

Margulis: It's flying. We may be right. It looks like there's no life on Mars.

SB: You'd better get specific. First of all, how does Viking overall look to you?

Margulis: It's an unbelievable success. Everything is working beyond their wildest dreams.

SB: How do the biology experiments look to you at this point?

Margulis: The thing is that if there's any problem, it's a problem in interpretation, rather than in technical problems, because the engineering's worked unbelievably well. They're getting good data, as good as conditions permit. Do you want me to tell you about it from the beginning?

SB: Sure.

Margulis: There are three experiments that are called the biology package, and there's a fourth experiment, more important than any of those for biology, and that is the GCMS, the Gas Chromatograph Mass Spectrometer. It is an instrument that was tuned up to look for organic carbon and organic nitrogen compounds, going up to molecular weights of 400 or so. There's not a piece of soil in the world you can pick up that it wouldn't detect organics in. In fact, you can just run your fingers across a piece of glass, and there's plenty of organic matter in your fingerprint to show up in that machine, because the sensitivity goes from parts per million to parts per billion of organic stuff. This is Klaus Biemann's instrument.

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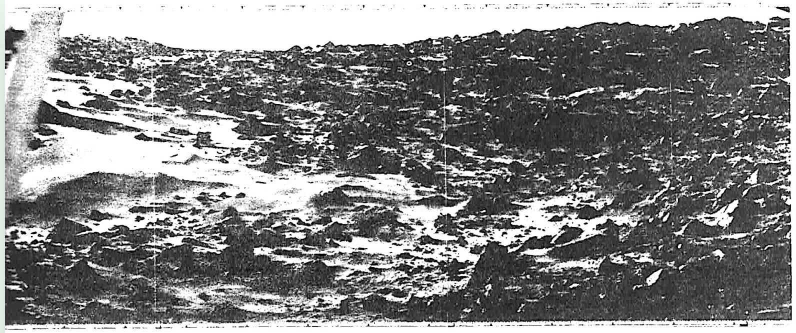
Margulis: . . .The chromatograph is very sensitive. . . . It's essentially seen no carbon except oxidized carbon, CO2 and CO, so any biology results have to be interpreted in the light of the fact that there's no evidence of organic compounds. Now, such organic compounds may be there, they could be under the surface or they could be hiding somewhere, but they're not in the samples.

SB: If they were in the atmosphere, would they be picked up?

Margulis: Oh yeah. They're not in the air by other criteria. Everything is in a very oxidized state. You know what happens to organic matter, it just burns, so the carbon is in CO and CO2, and that's very bad for organic material, those conditions.



7:30 a.m. on Mars, looking east from Viking I at a dune field. The boulder on the left is 25 feet away and measures about 3 feet by 10 feet.

The chromatograph is very sensitive, and it's hooked up to a mass-spectrometer which allows you to immediately look at the mass numbers, the number of atoms in whatever you see on the gas chromatograph. It's a double control on it — an excellent instrument. The point is that it's detected zero. That's NO organic compounds, no organic nitrogen or carbon compounds. Therefore all the biology experiments have to be looked at in that light, the fact that there's no organics in the samples at all.

SB: How many tests has the gas chromatograph made?

Margulis: As far as I know it's made two. One is a low-temperature run with stuff pyrolyzed — that is it's heated up without oxygen — and that gets almost all of the not-very-tightly-bound organics. That would give off all your amino acids and all kinds of small organic acids, if you ran it on an arbitrary soil sample on the Earth. And then they did a high temperature run, I think at 600° C, which will break up organic goop, tars and things they call kerogen and humic acids. High molecular weight incomprehensible materials get broken down into component parts, and you never know what the high molecular weight stuff is but you know what it yields. Both those runs were done with internal controls on them to be sure the instrument is working, and the instrument is definitely working. For example the instrument is seeing background atmospheric gases the same as the entry probes did, so it's definitely seeing things that are there.

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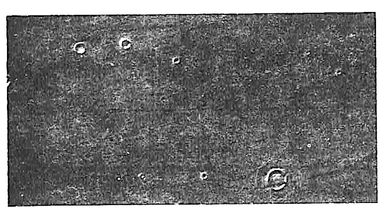

Viking I landing site on the Chryse plain.

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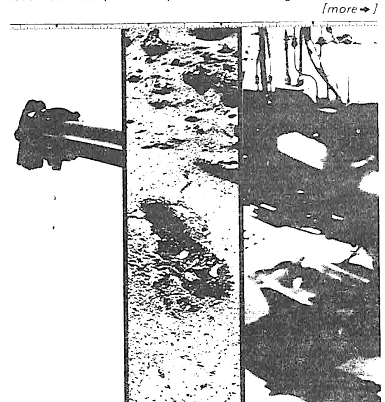
Most people feel that some organics ought to be on Mars because of meteorites. There's organic matter being brought in by meteorites, and we're not even detecting that. So that means that it's either been destroyed, or it's been preserved deeper down than the samples have gone.

SB: So the finding is even lower than expected?

Margulis: It's incredible. To me, it makes the biology much more easy to interpret, because it's a much more clear-cut negative result than I would have anticipated. I was anticipating a very low organic finding, which would be ambiguous, because you don't know whether that's from meteorites, or whether it's from pre-biotic processes, or what else. But in fact it's a moot point now, because the reading is zero.

[more →]



Viking I's telescoping scoop takes the first sample of Martian "soil" and dumps it in the hopper (right) for analysis.

Note. In this conversation, "organics" or "organic matter ... brought in by meteorites" refers to the elemental *building blocks* of living systems distributed throughout the abiotic cosmos—such as carbon, hydrogen, oxygen, nitrogen, or phosphorus—and not to the carbon-based compounds in the residues of living tissues that suffuse our biosphere.

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SB: If there were life you'd look for what gases?

Margulis: You'd look for ammonia, methane, hydrogen, or hydrogen sulfide or any of these things that are flagrant contradictions in the presence of oxygen and CO2. What you have on the Earth is this sort of flagrant contradiction which would, if left alone, go to a Martian type of state. The fact that you have these reduced gases on Earth with its oxygen-rich atmosphere means that they're constantly being produced by organisms. You don't have any of those kinds of contradictions on Mars at all. And that's why Jim and I are going to try to capitalize on the interest in this. . . .

SB: You sound pretty excited yourself.

Margulis: Well, Mars is interesting to me because it's kind of like a naked Earth. As soon as you get a consensus there's no life on Mars, that's where the ball game begins as far as I'm concerned. Because that's when we'll be able to define the ways in which we know life has modulated the Earth. But as long as someone's holding out that there's life on Mars that's modulating the planet, then we don't know how to subtract it, because it would be a totally different kind of life, and its effects would be unknown, and so on. I can't begin on the exercise. So I'm one of the few people, I guess Jim Lovelock too, who are really excited about a good negative result. What I would call this, if I were writing your article, is "The Three Billion Dollar Negative." I don't know if that's the right price, but it's some huge number like that.

SB: So Earth is alone.

Margulis: As far as the eye can see in the solar system, we're here by ourselves. When you start talking about life elsewhere, that's highly probable, but it's terribly distant, far outside the solar system.

pressure. The cold temperature per se you can survive in, but you can't metabolize in it, and there's only so long you can sit around waiting.

SB: How big a deal would it be to make the planet habitable, do you suppose?

Margulis: A big deal. A very big deal.

SB: If you carted in the stuff for the atmosphere . . .

Margulis: You're not going to increase the gravity, so you'd have trouble keeping it there. You'd have to have closed containers for atmosphere.

SB: In terms of Gaia, you made some predictions a while back that there'd be no life on Mars because of what you knew about the Martian atmosphere. Does the Martian atmosphere still pretty much have what you thought was in it?

Margulis: It has very much what we thought. It's got all those exhaust gases, all those highly oxidized states of carbon. I'm glad they found the nitrogen, 'cause now we have a number on it, but there's no reduced nitrogen in there, which you need. You see, there are no reduced compounds in the presence of the oxidized ones. Which is our clue. Everything's essentially oxidized.

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SB: What was your impression of the scene at JPL when you were there?

Margulis: People were pretty much ecstatic. There was the possibility of a crash landing, or of everything not working, but everything worked. They're really getting data, a lot of data. Everyone is up to their ears. I know that the biology team has been having 6 a.m. meetings. Everyone's exhausted, but elated. It's a regular high around there.

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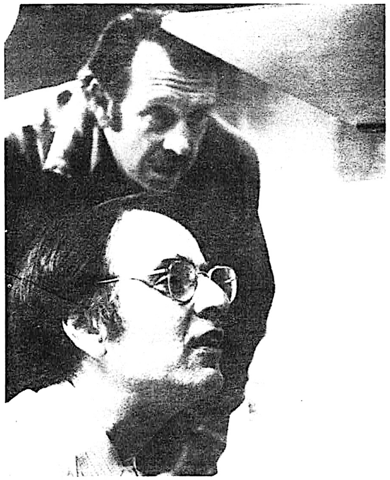
SB: What does this say about the delicacy of the position of Earth in relation to the Sun? Venus is just a bit closer and Mars is just a bit father, and if they're both dead, that puts us in a very narrow cambium.



July 20, 1976, Viking I landing. Carl Sagan viewing the first photographs from the surface of Mars on a TV monitor. Behind him, an ABC-TV cameraman. Carl was on various national networks practically all day.

Margulis: That's true, but on the other hand, it's known by anyone who's cared to think about it that for life to persist you've got to have open bodies of liquid water. I don't mean steam, and I don't mean ice, which excludes constant temperatures above boiling and below freezing. Life is essentially a variation on the theme of water.

SB: Do you know anybody else besides yourself and Lovelock who've formally predicted no life on Mars?

Margulis: That's a good question. You find someone else* and I'd be very interested. I never ran across it, but you know i don't really read Martian literature very much except what's sent to me that I have to read. I think that there's a general sentiment amonst astronomers that there probably isn't any Martian life, but I don't know if they've said that in any kind of intellectual framework or in a formal way. ◘

*In '67 Hitchcock & Lovelock made this prediction based on what we knew then of the atmosphere of Mars. —LM

CARL SAGAN

Stewart Brand: How's it look for Viking II right now?

Carl Sagan: Well, we had a hairraising time during entry because we lost communication with the orbiter, so it was sort of wild, but everything seems to be in fine shape there now. As far as I know, there are no malfunctions at all. We landed in a place with the promising name of Utopia. The landing site some people thought would be filled with small sand dunes, but there's nothing but rocks as far as the eye can see. Many of the rocks are quite strangely shaped, they may be aeolian ventifacts, rocks which are sculpted by sandblasting by windblown dust. Some of them certainly seem volcanic in origin.

SB: It looks enough different from the Viking I site to be interesting?

In the midst of the ongoing run of *CoEvolution Quarterly*, in October 1980 Stewart Brand brings out the *Next Whole Earth Catalog*, a massive (608 pp.) compendium of new content and previously published items from the Catalogs and CoEvolution Quarterlies. The previous year, James Lovelock published his first book, *Gaia: A New Look at Life of Earth* (Oxford, 1979), reviewed prominently here in the opening pages.

Say what you will about Brand's own intellectual and professional evolution, one thing is certain: he did understand whole systems. He got Gaia early on, and he largly got it right. Brand is also feeling somewhat burned by now by the blowback from the Space Colonies debate and other of his more recent heretical stances. Thus he underlined his appreciation for Lovelock's own resistance to knee-jerk environmentalism—as he implies in his headnote to the entry on Lovelock's book, they share an aversion to "the simplistic thinking that goes on in the environmental movement."

Next Whole Earth Catalog (October 1980)

Gaia

This may turn out to be one of the epochal insights of this century: that the entire life of Earth, through its atmosphere and ocean, functions effectively as one self-regulated organism: Gaia (after the Greek Earth goddess).

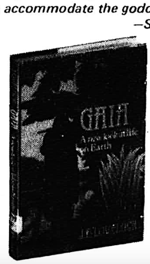
Free-lance British scientist James Lovelock is the originator of the hypothesis (along with American microbiologist Lynn Margulis). As might be expected from a mind with the range to encompass the material requisite for the Gaian recognition, Lovelock writes a winning prose. This is a brief, personal, convincing performance. It even overcomes my lifelong aversion to chemistry, making fascinating sense of the difference between the chemical equilibrium of a dead planet and the chemical steady state of a live one.

Along the way Lovelock has astute criticism for some of the simplistic thinking that goes on in the environmental movement — as, for example, the premature hysteria over the effect of aerosol sprays on the ozone layer (a problem Lovelock helped discover). He notes that from Gaian perspective we are over-concerned with industrial pollution and under-concerned with protecting the integrity of the all-important tropical jungles and continental shelves of the sea. The health of Gaia is far more endangered by our agriculture than our industry.

As science and as poetry, Gaia (pronounced "gúy - a") is a major planetary self-discovery. It's likely that all our thinking will be re-oriented to accommodate the goddess.

—SB

Gaia
(A new look at life on Earth)
J.E. Lovelock
1979; 157 pp.
$11.95 postpaid from:
Oxford University Press
16 - 00 Pollitt Drive
Fair Lawn, NJ 07410
or Whole Earth Household Store



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By now a planet-sized entity, albeit hypothetical, had been born, with properties which could not be predicted from the sum of its parts. It needed a name. Fortunately the author William Golding was a fellow-villager. Without hesitation he recommended that this creature be called Gaia, after the Greek Earth goddess also known as Ge, from which root the sciences of geography and geology derive their names. In spite of my ignorance of the classics, the suitability of this choice was obvious. It was a real four-lettered word and would thus forestall the creation of barbarous acronyms, such as Biocybernetic Universal System Tendency/Homeostasis. I felt also that in the days of Ancient Greece the concept itself was probably a familiar aspect of life, even if not formally expressed. Scientists are usually condemned to lead urban lives, but I find that country people still living close to the earth often seem puzzled that anyone should need to make a formal proposition of anything as obvious as the Gaia hypothesis. For them it is true and always has been.

Gas	Planet			
	Venus	Earth without life	Mars	Earth as it is
Carbon dioxide	98%	98%	95%	0.03%
Nitrogen	1.9%	1.9	2.7%	79%
Oxygen	trace	trace	0.13%	21%
Argon	0.1%	0.1%	2%	1%
Surface temperatures °C	477	290±50	−53	13
Total pressure bars	90	60	0064	1.0

Table 3. Some chemically reactive gases of the air

Gas	Abundance %	Flux in megatons per year	Extent of disequilibrium	Possible function under the Gaia hypothesis
Nitrogen	79	300	10^{10}	Pressure builder Fire extinguisher Alternative to nitrate in the sea
Oxygen	21	100,000	None. Taken as reference	Energy reference gas
Carbon dioxide	0.03	140,000	10	Photosynthesis Climate control
Methane	10^{-4}	1,000	Infinite	Oxygen regulation Ventilation of the anaerobic zone
Nitrous oxide	10^{-5}	100	10^{13}	Oxygen regulation Ozone regulation
Ammonia	10^{-6}	300	Infinite	pH control Climate control (formerly)
Sulphur gases	10^{-8}	100	Infinite	Transport gases of the sulphur cycle
Methyl chloride	10^{-7}	10	Infinite	Ozone regulation
Methyl iodide	10^{-10}	1	Infinite	Transport of iodine

Note: Infinite in column 4 means beyond limits of computation

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The start of the Gaia hypothesis was the view of the Earth from space, revealing the planet as a whole but not in detail. Ecology is rooted in down-to-Earth natural history and the detailed study of habitats and ecosystems without taking in the whole picture. The one cannot see the trees in the wood. The other cannot see the wood for the trees.

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Considered solely as a life-detection experiment, atmospheric analysis was, if anything, too successful. Even then, enough was known about the Martian atmosphere to suggest that it consisted mostly of carbon dioxide and showed no signs of the exotic chemistry characteristic of Earth's atmosphere. The implication that Mars was probably a lifeless planet was unwelcome news to our sponsors in space research.

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If we are a part of Gaia it becomes interesting to ask: "To what extent is our collective intelligence also a part of Gaia? Do we as a species constitute a Gaian nervous system and a brain which can consciously anticipate environmental changes?"

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Towards the end of 1975 the United States National Academy of Sciences issued a report prepared by an eight-man committee of their own distinguished members, assisted by forty-eight other scientists chosen from those expert in the effects of nuclear explosions and all things subsequent to them. The report suggested that if half of all of the nuclear weapons in the world's arsenals, about 10,000 megatons, were used in a nuclear war the effects on most of the human and man-made ecosystems of the world would be small at first and would become negligible within thirty years. Both aggressor and victim nations would of course suffer catastrophic local devastation, but areas remote from the battle and, especially important in the biosphere, marine and coastal ecosystems would be minimally disturbed.

To date, there seems to be only one serious scientific criticism of the report, namely, of the claim that the major global effect would be the partial destruction of the ozone layer by oxides of nitrogen generated in the heat of the nuclear explosions. We now suspect that this claim is false and that stratospheric ozone is not much disturbed by oxides of nitrogen. There was, of course, at the time of the report a strange and disproportionate concern in America about stratospheric ozone. It might in the end prove to be prescient, but then as now it was a speculation based on very tenuous evidence. In the nineteen-seventies it still seems that a nuclear war of major proportions, although no less horrific for the participants and their allies, would not be the global devastation so often portrayed. Certainly it would not much disturb Gaia.

The report itself was criticized then as now on political and moral grounds.

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From a chemical viewpoint, although not in terms of abundance, the dominant gas of the air is oxygen. It establishes throughout our planet the reference level of chemical energy which makes it possible, given some combustible material, to light a fire anywhere on the Earth. It provides the chemical potential difference wide enough for birds to fly and for us to run and keep warm in winter; perhaps also to think. The present level of oxygen tension is to the contemporary biosphere what the high-voltage electricity supply is to our twentieth-century way of life. Things can go on without it, but the potentialities are substantially reduced. The comparison is a close one, since it is a convenience of chemistry to express the oxidizing power of an environment in terms of its reduction-oxidation (redox) potential, measured electrically and expressed in volts. It is in fact no more than the voltage of a hypothetical battery with one electrode in the oxygen and the other in the food.

"This may turn out to be one of the epochal insights of this century: that the entire life of Earth, through its atmosphere and ocean, functions effectively as one self-regulated organism....

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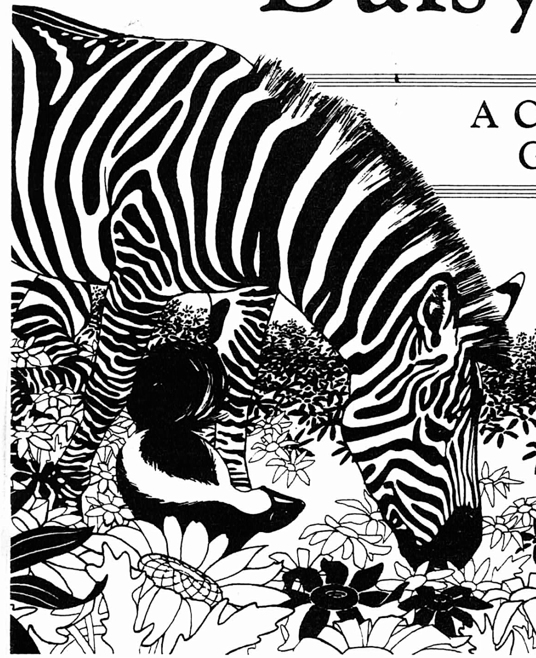
"As science and as poetry, Gaia... is a major planetary self-discovery. It's likely that all our thinking will be re-oriented to accommodate the goddess." —SB

BC] "Cybernetics for Lovelock is set at control systems engineering and, notwithstanding occasional perturbations, stays at that steady conceptual state. His invention of the Daisyworld simulation brings out his ties to computational platforms for cybernetic model building. Daisyworld—a computer model of homeostatic self-regulation in the coupled interaction between an idealized biota and its virtual environment—is the culmination of Lovelock's heuristic exploration of Gaian parameters through cybernetic models" (*Gaian Systems* 132).

"Since cybernetics was kidnapped by computer science a couple decades back **[!!]**, there have been few working applied cyberneticians loose in the world. Lovelock, holder of innumerable patents in gas chromatography and related fields, visiting professor in the Department of Cybernetics at Reading University, is one. May he and Gaia inspire more." (SB)

Daisy World



TOM PARKER

A Cybernetic Proof of the Gaia Hypothesis

by *James E. Lovelock*

IT IS NOW JUST OVER TEN YEARS since Lynn Margulis and I published our first paper on the Gaia Hypothesis.[1] You may be wondering what has happened in the meanwhile.

You will have noted that the idea does not yet seem to have set big science on fire. This is not too surprising, for many famous scientists in the past, including such names as Redfield, Hutchinson, and Sillen, touched on the idea without managing to convince their colleagues. One of the extraordinary things about science is that whilst it swallows the intricacies of relativity and of genetics, it has never been comfortable with whole systems; witness the unpopularity of cybernetics. How

In his book **Gaia: A New Look at Life on Earth** **(NWEC** *p. 7) British scientist Lovelock defines the Gaia Hypothesis so:*

"It postulates that the physical and chemical condition of the surface of the Earth, of the atmosphere, and of the oceans has been and is actively made fit and comfortable by the presence of life itself. This is in contrast to the conventional wisdom which held that life adapted to the planetary conditions as it and they evolved their separate ways."

As Lovelock notes, there is a peculiar silence going on. Lovelock is widely respected, his book got warm reviews in **Scientific American, Science,** *and such places, and the Gaia Hypothesis is well known and well regarded. But it is not being challenged — or even discussed — in the scientific literature. In a computer teleconference I'm in I raised the subject, and British anthropologist Mary Douglas had this to say:*

"Why should people who are really worried about nonrenewable resources and irreversible damage to the environment take so little notice of a well thought out, optimistic message? . . . . You might start by generalizing the problem, and ask why pessimistic theories are more readily credited than optimistic ones in this part of the century . . . . What are the funding agencies looking for? Trouble-shooting research. There is this problem here, or that problem there. The competitive research tenders have to show that they can see the urgent problems and that their project might solve one of them . . . . That is why no one has had time to look at Gaia's hopeful scenario."

Since cybernetics was kidnapped by computer science a couple decades back, there have been few working applied cyberneticians loose in the world. Lovelock, holder of innumerable patents in gas chromatography and related fields, visiting professor in the Department of Cybernetics at Reading University, is one. May he and Gaia inspire more.

"Daisy World" is so simple a proof you could run it on your, um, personal computer. Jim did.

This article is rewritten from a recent collection of papers, **Biomineralization and Biological Metal Accumulation** *(1982, $69.50 postpaid from Kluwer Boston, 160 Old Derby Street, Hingham, MA 02043).* —*Stewart Brand*

"One of the extraordinary things about science is that whilst it swallows the intricacies of relativity and of genetics, it has never been comfortable with whole systems; witness the unpopularity of cybernetics. How many universities, I wonder, have departments of cybernetics?"

CoEvolution Quarterly (Summer 1983)

"I suspect that most scientists still reason in the cause-and-effect manner set by Aristotle. The circular and recursive logic of whole systems is alien to them. This is especially true of geologists, geochemists, biochemists, and exobiologists who might otherwise have been interested in Gaia.

"It is true that engineers and physiologists are enlightened by their professional need to lift themselves from the narrow trough of linear thought. Unfortunately they tend to keep the conspicuous advantages of whole systems thinking to themselves."

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The only constructive criticism we have so far received is from biologists, notably Ford Doolittle in **CoEvolution**[2] and Richard Dawkins in his recent book.[3] Both of them thought that Gaia could not exist, for altruism global in scale would require foresight and planning by the biota, which is inconceivable.

The purpose of this article is to review the evidence for Gaia and to present a simple model, called "Daisy World," specifically developed to show that global homeostasis does not need foresight or planning by life.

What is Gaia?

The Gaia Hypothesis arose directly from the planetary exploration programme of NASA. There was a need to discover in advance of a landing mission whether or not a planet such as Mars bore life. In 1966 Dian Hitchcock[4] was able to show that information on the atmospheric composition of a planet was sufficient as prima facie evidence of life. The method was based on the high probability that planetary life, through its use of the atmosphere, would drive the chemical composition of this medium far from the near-equilibrium steady state of a lifeless planet. This detection method when applied to Mars strongly indicated it to be barren, a conclusion highly unacceptable to exobiologists at that time. The same method applied to the Earth indicated the near certainty of the presence of life. It also suggested that the atmosphere was more than just a biogeochemical mixture. It appeared to be actively maintained in composition at close to an optimum by and for the biota. This way of thinking about the planets was a stunning discouragement for exobiologists whose scientific inspiration came from the search for life outside the Earth. Some part of the tendency by space scientists to ignore the joyous counterpart of this approach, the discovery of Gaia, perhaps arose from their disappointment.

The evidence drawn from atmospheric compositions which points to life and to a control system on a planet is summarised in **Figures 1 and 2**, which show the abundances and the fluxes, respectively, of the gases of the present atmosphere compared with those of an abiological Earth. From these diagrams it is clear, as has been argued in previous papers, that the atmosphere is a highly reactive mixture which would but for life rapidly revert to the stable inert condition of the abiological state. It is the intense disequilibrium of the atmosphere which advertises the presence of life on Earth. It is the maintenance of this reactive and unstable

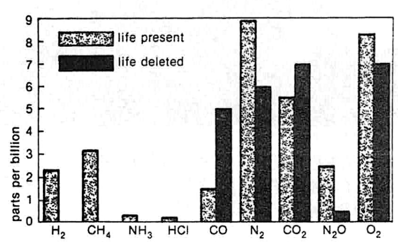

Figure 1. The abundance of gases in the present atmospheric gas flux compared with that expected of the abiological steady state.

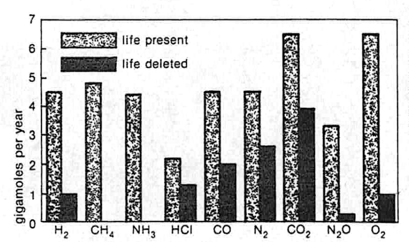

Figure 2. The fluxes of gases (gigamoles per year) through the present atmosphere compared with those expected for the abiological steady state.

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"**Many geochemists** now accept that the Earth's surface features are a result of the coevolution of the biota and the rocks. But they **still see the association between life and its environment as passive**. Life adapts to environmental change and the evolution of life may change the environment, but any feedback, negative or positive, between these processes is passive. **In sharp contrast the Gaia Hypothesis sees the Earth as homeostatic, with the biota actively seeking to keep the environment optimal for life**."

—Recall the distinction made in "Behavior, Purpose, and Teleology" between active and passive behaviors: "Active behavior is that in which the object is the source of the output energy involved in a given specific reaction. . . . In passive behavior . . . all the energy in the output can be traced to the immediate input."

It is the intense disequilibrium of the atmosphere which advertises the presence of life on Earth. It is the maintenance of this reactive and unstable atmosphere at a steady state for times much longer than the residence times of individual gases that suggests the presence of a control system, Gaia.

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Feedback and Homeostasis

Many geochemists now accept that the Earth's surface features are a result of the coevolution of the biota and the rocks. But they still see the association between life and its environment as passive. Life adapts to environmental change and the evolution of life may change the environment, but any feedback, negative or positive, between these processes is passive. In sharp contrast the Gaia Hypothesis sees the Earth as homeostatic, with the biota actively seeking to keep the environment optimal for life.

The first intimation of Gaia comes from the realisation that every evolutionary step of the biota must to a greater or lesser extent alter the environment in which the next generation will evolve. If the change is to a more favourable global environment then it will carry more progeny and the environmental change will be reinforced. In the same way a less favourable environment will carry less progeny and hence their unfavourable attributes will become attenuated.

It is not immediately obvious how such a course of events could lead to planetary homeostasis. As Ford Doolittle observed, the biota have no capacity for conscious foresight or planning and would not in the pursuit of local selfish interests evolve an altruistic system for planetary improvement and regulation.

The sequential logic of descriptive writing is not designed for the concise explanation of control systems with their inherent circularity, recursiveness, and nonlinearity. Even the formalism of mathematics loses its elegance when an attempt is made to describe a simple nonlinear control system such as, for example, an electrical water heater controlled by a bimetallic strip thermostat. I have chosen therefore to present a simple model of an imaginary planet whose temperature is regulated at a biological optimum over a wide range of solar radiation levels as a working example of a Gaian mechanism.

Before describing this model it is useful first to consider the terms *active*, *passive*, and *feedback* in the context of their origin, namely systems engineering. **Figure 3** illustrates graphically the change of some intrinsic property of a system, such as temperature, with time when there is a constant flux of a related quantity such as heat. The diagonal line across the diagram represents the rate of rise of temperature of an inert body during the constant input of heat. Line (B) illustrates passive negative feedback such as might occur on a watery planet as a result of increasing cloudiness. Line (A) illustrates passive positive feedback such as could take place when an ice-covered planet reached the melting point of water and its albedo changed from near 1.0 to a much lower value associated with open oceans and crustal rock. Line (C) is for an active feedback system with the goal of maintaining a set temperature.

With the passive negative feedback some constancy is achieved but at a value arbitrarily set by the properties of water and which cannot be changed. With the active system, constancy is possible at any chosen

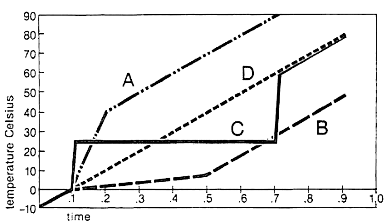

Figure 3. Passive negative and positive feedback processes, and active homeostasis. Energy is supplied at a constant rate to an object of unknown thermal mass. Line B illustrates passive negative feedback on the energy supply over a limited range. Line A represents passive positive feedback over the same range, and line C illustrates active regulation at a chosen set temperature. Diagonal line D shows the rate of temperature rise of an inert object.

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Daisy World illustrates how the powerful capacity of life to grow until a niche is full acts as an amplifier, and natural selection acts as a sensor, in a control system which is able effectively and precisely to regulate planetary temperature at close to the optimum for the specified life form. No foresight or planning is required by the daisies, only their opportunistic local growth when conditions favour them.

value. Positive feedback is used constructively so as rapidly to reach the chosen level and negative feedback used to keep the constancy. Furthermore the chosen set point can itself evolve as part of a more intricate system of evolutionary change.

Walter B. Cannon coined the term *homeostasis* for those coordinated physiological processes which maintain most of the steady states of a living organism. Homeostasis is very much an active process, one in which any departure from the chosen state is sensed and the difference between preference and reality amplified and used to oppose the perturbation and so restore the status quo. The stability of such a system, the quality of its homeostasis, is measured by its capacity to withstand perturbations.

Now let us see how active regulation of a planetary scale might be achieved by the biota without the need for them to have foresight or receive divine assistance.

Daisy World

The dominant plant life of Daisy World are black and white daisies. They are grazed by grey cattle but both producers and consumers flourish when the climate permits. Both species of daisy are identical in every respect other than the colour of their flowers and their growth varies with temperature in the same way. Because they absorb more radiation the local temperature of a stand of black daisies will always be higher than that of a stand of white daisies. As a result the rates of growth of the two species will be different at any given intensity of sunlight. To model this planetary ecosystem let us assume that the two species of daisy have a growth rate (Beta) which varies with temperature parabolically as follows:

$$\text{Beta} = A + BT - CT^2$$

Where (A), (B) and (C) are constants chosen so that growth is zero at below 5 and above 35 degrees Celsius and a maximum at 20 degrees. These limits are those that determine the growth of most contemporary vegetation. Under cool conditions the growth of the black daisies, which are locally warmer than are the white, will be favoured. Under hot conditions the white daisies will have the advantage. The rate of spread of one species into the zone of the other is given by a relationship described and experimentally confirmed by Carter and Prince as follows:

$$dy/dt = \text{Beta}\ xy - \text{Gamma}\ y$$

Where (x) is the number of susceptible sites for growth and (y) is the number of infective sites. Beta and Gamma are the growth and death rates respectively.

Daisy World is a cloudless planet with no greenhouse gases. **Figure 4** illustrates the response of the mean planetary temperature with increasing solar luminosity. The dotted line illustrates the temperature of a barren planet and the solid line when the daisies are present. Daisy World illustrates how the powerful capacity of life to grow until a niche is full acts as an amplifier, and natural selection acts as a sensor, in a control system which is able effectively and precisely to

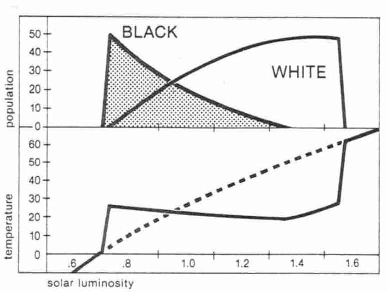

Figure 4. The active regulation of planetary temperature during the increase of solar luminosity by the growth and natural selection of two species of daisy. White daisies, albedo 0.7 and black daisies, albedo 0.3. The albedo of the bare planetary surface is taken as 0.5. The solid line below is the regulated mean planetary temperature.

BC] “Daisyworld’s nonlinear equations model a rudimentary planetary system, steadily forced, as is ours, by a sun gradually gaining in luminosity, whose biota are minimally composed of black daisies that thrive in cool conditions and white daisies that thrive when it’s hot. Seeded with both varieties, Daisyworld starts out cool and is then externally forced toward warmer conditions. Due to their different albedos, or indexes of reflectivity, the two kinds of daisies feed back upon their climate to different effects. The low-albedo black daisies heat the planet by absorbing the sun’s rays, while the high-albedo white daisies cool the planet by reflecting that same radiation back to space. The black daisies thrive at first as the initially cool conditions suppress the growth of the white daisies. But as the black daisies proliferate, the planet warms up enough to favor the spread of white daisies and suppress the growth of black daisies. The rising tide of white daisies diminishes the black daisies while also reflecting heat away from the planet. . . .”

Lynn Margulis: "There perturbations are tests of Gaia, and the system bounces back."

BC, con't.] ". . . These countereffects settle down or regulate the positive amplification between the sun and the black daisies that had been driving up the temperature. Pushing back on the absorption of solar forcing, Daisyworld as a whole maintains its virtual climate at a steady level for as long as it can. It does so automatically, with no teleological impetus but only the mutual interplay of negative and positive feedbacks: 'No foresight or planning is required by the daisies, only their opportunistic local growth when conditions favor them.' The black and white daisies model the mutual coupling of two Gaian feedback loops, either of which can exert a negative—that is, regulatory or stabilizing—effect on the other to achieve and conserve a virtual homeostasis, up until the model's solar forcing becomes too great for the system to control. Driven past that tipping point, Daisyworld's life goes extinct" (*Gaian Systems* 135).

regulate planetary temperature at close to the optimum for the specified life form. No foresight or planning is required by the daisies, only their opportunistic local growth when conditions favour them.

This type of model is not limited to the very artificial conditions of Daisy World. A more general version would take into account the possibility that once life appears on a planet geochemical evolution will be limited by the circumscribed set of physical and chemical constraints which characterize the biota. Any external or internal chemical or physical change away from this set of conditions will lead not only to adaptation but also to the selection of those organisms whose growth alters the environment so as to oppose the unfavourable development.

Past, Present and Future

The Gaia Hypothesis postulates the existence of active systems for the chemostasis and thermostasis of the planetary environment. It predicts that the environment has been and will be stable and constant in spite of perturbations, whether sudden or from some continuous and progressive change. Strong support for the hypothesis will therefore come from the discovery of instances where there was clear evidence of the rapid and effective restoration of homeostasis after known perturbations.

There are several examples of major perturbations during the course of the history of life on Earth. The first and possibly the greatest was the origin of life itself. Whatever the environment was before life it should have changed profoundly soon after the planet was colonised. We know that conditions were favourable at the start of life so it is worth asking the question: How was it that these conditions remained favourable in spite of the inevitable changes in surface, ocean, and atmospheric composition imposed by life? Thus the use of CO_2 as a carbon source by early photosynthetic life could have gravely disturbed the precarious radiation balance of the Earth when warmed by a cooler sun. It is interesting therefore to speculate on the composition of the Archean atmosphere after life began. There is evidence to suggest that the rate of carbon burial in the Archean was not greatly different from now. Much of the carbon entering present-day anoxic sediments is returned to the atmosphere as methane. If the Archean production of methane was comparable with that which is now produced, and bearing in mind that none of it would be oxidised by consumers in the anoxic Archean oceans, the flux to the atmosphere could have been substantial. In addition to methane, sulphur gases and possibly even nitrous oxide may also have been flowing into the Archean atmosphere. It would need a general circulation model to predict such an atmosphere in detail. But it can be speculated that the troposphere would have a net reducing tendency with abundant polyatomic organic gases present. The radiative properties of such an atmosphere would solve the infrared problems of less CO_2 and also serve if necessary to filter out ultraviolet radiation at wavelengths less than 300 nanometres. The well-established glaciation coincident with the first appearance of oxygen in the atmosphere at 2.2 billion years ago is consistent with the oxidative destruction of these organic gases.

The emergence of oxygen as an atmospheric gas may have been the largest perturbation the Earth has yet experienced. Significantly it was internally and biologically driven. The process of photosynthesis, whereby oxygen and carbon are segregated and some of the carbon becomes buried, ineluctably drove the planetary surface to ever more oxidising during the Archean. It is true that some of this tendency was offset by the return of reducing materials by tectonic processes, but until the critical problems posed by the presence of gaseous oxygen began to exert their effect on selection, oxidation proceeded unchecked.

Among the minor but startling problems posed by the appearance of oxygen would have been the speciation of the element

"The emergence of oxygen as an atmospheric gas [during the "Great Oxidation Event" (GOE)] may have been the largest perturbation the Earth has yet experienced. Significantly it was internally and biologically driven. The process of photosynthesis, whereby oxygen and carbon are segregated and some of the carbon becomes buried, ineluctably drove the planetary surface to ever more oxidizing [i.e. increase of ambient oxygen] during the Archean [eon]. It is true that some of this tendency was offset by the return of reducing materials [e.g. hydrogen and methane, which react with oxygen to remove it from the air] by tectonic processes, but until the critical problems posed by the presence of gaseous oxygen began to exert their effect on [natural] selection, oxidation proceeded unchecked [and so radically altered the biosphere]."

uranium. In the reduced form uranium is safely locked as water insoluble material dispersed in a great dilution. In an oxidising environment uranium is water soluble and readily concentrated by microorganisms. This task was once successfully completed by microorganisms resident at a region which is now Gabon in Africa about 2.2 billion years ago. As a result a nuclear reactor commenced operation and ran for several million years. At that time uranium was substantially richer in the fissionable isotope U235 than now. In those days a nuclear reaction did not require the skill of a Ph.D. for its assembly; dumb bugs could do it. It is fortunate that the Earth did not become oxidising in the early Archean, for then the uranium was enriched close to bomb quality. Spectacular nuclear fireworks might have been more than the infant Gaia could have withstood.

By the time the metazoan biota were well established the presence of charcoal in the sediment provides a fossil record of ancient fires. The range of atmospheric oxygen over which fires can take place yet not be so devastating as to threaten all standing vegetation is 15 to 25 percent by volume. It is therefore tolerably certain that atmospheric oxygen has never ranged beyond these bounds in the last several hundred millions of years. This is a truly remarkable feat of regulation, for in the previous 90 percent of the Earth's history the pE has risen by at least ten units but is now held precisely constant. The mechanism by which oxygen is regulated is not yet known although we have proposed that the control of the proportion of carbon buried in the anoxic sediments, and hence the oxygen abundance, is achieved through the regulation of the venting of methane to the atmosphere. Interestingly, fires themselves exert a positive feedback on oxygen since carbon as charcoal is resistant to digestion by microorganisms and hence more is buried.

Throughout the existence of life on Earth there have been frequent collisions with planetisimals several kilometres in diameter, the most recent 65 million years ago. The impact energy of these collisions is vast enough to have caused major, albeit temporary, environmental changes, and was proposed by Alvarez and his colleagues as the cause of species extinctions in the fossil record.[5] **Figure 5** illustrates the impact craters so far discovered on the Canadian shield. Most of the events recorded by the craters represent an energy yield at the Earth's surface about 10^8 times larger than the detonation of the present global stocks of nuclear weapons. Although the consequences of these impacts are not yet known in detail they do act as impulse tests of the "black box" system. If and when a detailed description of the sequence of events at one of these collisions is uncovered it will chart the course of the perturbation and the rapidity and effectiveness of the return to an optimum environment which follows. It could provide important evidence about the existence and the nature of Gaia.

A progressive change in the environment which spans the past, present, and future is that which relates to the climate of the Earth. One of the more certain conclusions of astrophysics is that stars increase their radiation flux as they age. There is a consensus among astronomers that the sun was very probably about 25 percent less luminous at the Earth's origin than it is now. We know from the geological record that fluid water has always been present and from the origin of life that the climate cannot have been very different from now 3.5 billion years ago. In this context glaciations represent only minor departures from climatic constancy. Walker[6] proposed that a progressive decrease in atmospheric CO_2 from about 10 percent abundance at the start of life to the present 0.03 percent could through a decreasing greenhouse effect compensate for the progressive increase of solar luminosity. Although by itself carbon dioxide does not provide a very effective greenhouse, on the Earth its influence is amplified by the presence of abundant water vapor.

The mechanism by which CO_2 is varied inversely with the solar luminosity so as to maintain a constant temperature is the weathering of exposed calcium silicate rock. This is the only major sink for CO_2 from the atmosphere, and the rate of weathering has a positive temperature coefficient. Walker's proposal provides a plausible abiological mechanism for climatic and CO_2 regulation,

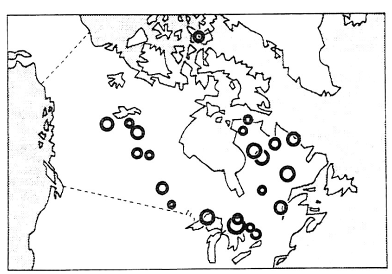

Figure 5. Map showing the impact craters so far discovered on the Canadian shield.

BC] Lovelock's unusually critical tone and pro-whole systems polemic in this article resonate with the countercultural cybernetics of *CoEvolution Quarterly*. Moreover, it may be that by now, in 1983, they also come with a taste of the Lindisfarne Association, which alternative countercultural gathering inducted Lovelock and Margulis together in 1981. We will examine this intellectual context in our next session. Meanwhile, we should note that while Margulis would occasionally expound Daisyworld in her own updates on Gaia theory, she herself did not sign on to it as a way of doing Gaian science. Rather, after encountering Maturana and Varela at Lindisfarne, her applications of autopoietic systems theory to Gaia's description read like a counterstatement on her part, implicitly aimed at Lovelock, with regard to a more refined biological route to the "circular and recursive logic of whole systems" that Lovelock rightly sees in Gaia. In this pursuit, Margulis would cultivate the Lindisfarne ethos for her own round of polemical interventions on behalf of autopoietic Gaia.

although with the present information on the fluxes of CO_2 it appears to be only partially able to account for the constancy of the climate throughout the Earth's history.

I do not disagree with the general basis of this interesting abiological control mechanism which would make Gaia redundant but wondered instead how much better it would work if life was included as a part of it. The real world is not abiological and the weathering of calcium silicate is very much a biological concern. At all levels from prokaryotic microorganisms to large trees and soil-moving animals the biota participates in the process of rock digestion. The partial pressure of CO_2 in the soil is 10 to 40 times greater than it is in the air. CO_2 is actively pumped from the air by the biota to those regions of the soil where it can react with calcium silicate particles. The rate of CO_2 fixation by plants is a strong function of both temperature and light intensity.

The need to have the biota participate in such a system is best illustrated by considering the consequences of its absence. If all life were deleted the soil CO_2 concentration would rapidly fall to below the present atmospheric level and weathering would be substantially reduced in rate. The input of CO_2 to the atmosphere from volcanoes is on average constant and consequently the atmospheric CO_2 concentration would rise until the current rate of weathering was reestablished. The new equilibrium level would probably be above the current levels of the soil, about 1 percent. This is because diffusion from the air is very slow compared with the active penetration of the soil by plant roots. The ambient temperature under these conditions was calculated by Lovelock and Watson to be about 20 degrees Celsius higher than now. The higher temperature might increase the abiological weathering rate but only slightly if it is limited by the rate of diffusion of CO_2 to the calcium silicate rock. Furthermore as recently modelled by Shukla and Minz[7] the lack of land life would so disturb the planetary water vapour transport that large areas would become desert where the weathering rate would be much reduced. It is also significant that CO_2 transport to and from the oceans is very dependent upon the presence of life. The deletion of life from the oceans would lead to a further increase in atmospheric CO_2.

Atmospheric CO_2 abundance and climate is a current environmental concern as a result of the geochemically minor perturbation attributable to fossil fuel combustion. **Figure 6** from Lovelock and Whitfield summarizes in simple diagrammatic form the rise of solar luminosity during the Earth's history and the fall of CO_2 abundance needed to compensate for this rise in heat flux.

The most interesting feature of this diagram is its suggestion that a new perturbation of major magnitude is, on a geological time scale, imminent. If the climate is to stay constant at near the optimum for the biota, then the CO_2 must be further reduced. However, a reduction below 100 ppm could not be suffered by most of the contemporary photosynthesisers. The diagram illustrates that such a level will be reached in only 100 million years. If zero CO_2 were tolerable even this is approached in 200 million years.

It is unlikely that our descendants will be there to witness this interesting period when it comes. The past history of the Earth suggests that a near optimal planetary environment will be sustained by some other means. ■

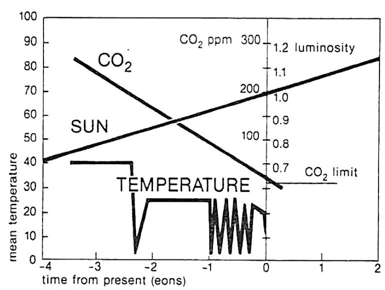

Figure 6. Evolution of the climate showing the variation of solar luminosity, with its present value taken as 1.0. Also illustrated on the same time scale are the proposed decline in carbon dioxide concentration, expressed as the square root of its concentration in ppmv and the approximate range of mean surface temperatures in degrees Celsius.

Footnotes

1. "Atmospheric Homeostasis by and for the Biosphere: The Gaia Hypothesis," J.E. Lovelock and Lynn Margulis, **Tellus**, 26:2, 1973.
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3. **The Extended Phenotype**, Richard Dawkins, p. 114, 1982, 320 pp., $22.95 postpaid from W.H. Freeman, 660 Market Street, San Francisco, CA 94104.
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5. I.W. Alvarez, W. Alvarez, F. Asaro, H.V. Mitchell, **Science**, 208, 1980, p. 1095.
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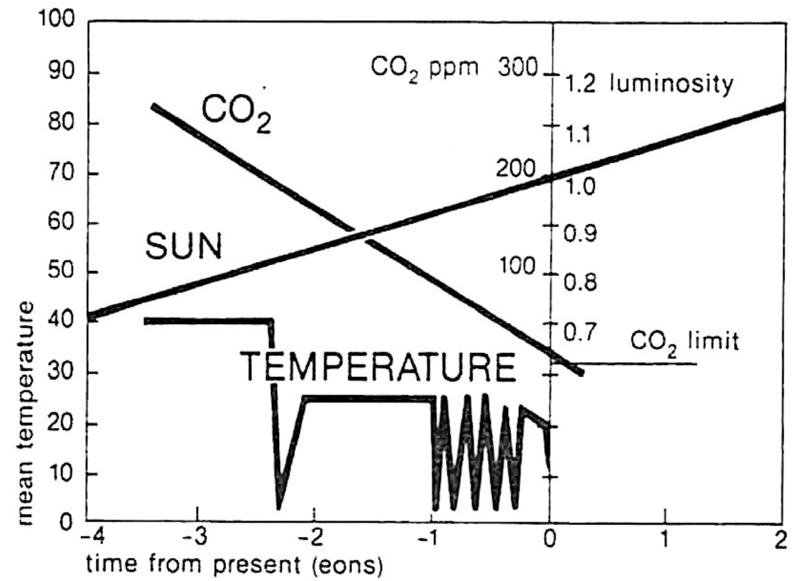

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