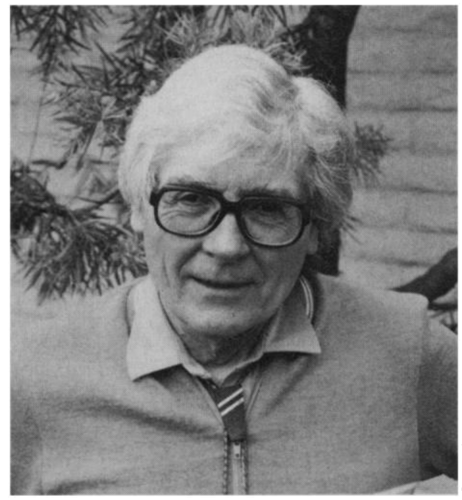
No Longer Willful, Gaia Becomes Respectable

The Gaia hypothesis, that Earth is a single huge organism intentionally creating an optimum environment for itself, has been made more palatable; interesting science is coming of it



The father of Gaia. *James Lovelock, Ph.D. in medicine, chemist, inventor, and independent scientist, works out of his home's barn-turned-laboratory at Coombe Mill, St. Giles on the Heath, Launceston, Cornwall.*

San Diego

GAIA is dead. Even her creator has rejected this concept of a superorganism striving to create and maintain conditions perfectly suited to the flourishing of life. Her final demise came last month at the first establishment-sponsored meeting to focus on her, but, phoenix-like, a new Gaia rose up, stripped of the original's intention and purpose but still holding sway over Earth.

Eco-extremists had loved the old Gaia, which had been named after the Greek goddess of Earth, but mainstream scientists never would get close to her. The new Gaia is little more appealing to most scientists than the old, but the existence of a major Gaia conference sponsored by the American Geophysical Union and attended by numerous prominent researchers points up the growing interest in the interaction between life and nonlife. Life may not control climate, for example, intentionally or by chance, but it surely participates in the climate system, everyone agrees. Life also clearly affects the composition of the sea and the air. Recent discoveries prompted by the Gaia hypothesis may even lead to the elucidation of new links between life and its surroundings.

James Lovelock, Gaia's creator, felt compelled to hypothesize a complex of controlling interactions between life and nonlife when he considered how remarkably well life has fared. "The climate and the chemical properties of the Earth now and throughout its history," he wrote in his recently reprinted 1979 book, "seem always to have been optimal for life." This relative stability persisted despite the sun brightening 30% since Earth formed, volcanoes spewing acid for eons, and green plants polluting the atmosphere with toxic oxygen, among other apparent abuses. "For this to have happened by chance is as unlikely as to survive unscathed a drive blindfold through rush-hour traffic," Lovelock claimed.

Because the serendipitous interactions of chemistry and physics would presumably fail to ward off the lethal extremes of ice, corrosion, and poisoning, Lovelock proposed that, like the human body, life as a whole maintains optimum conditions for itself, a tendency called homeostasis. The sum total of the living and nonliving components of this system Lovelock called Gaia. (The name has been pronounced guy'a, as in classical Greek.)

The proper study of Earth would thus be geophysiology, the dissection of the numerous circuits through which information flows in both directions as the living entity of Earth senses changes and directs adjustments to counter those changes. As the sun warmed over the eons, for example, life would have intervened. It would have withdrawn from the atmosphere the carbon dioxide that, through the greenhouse effect, had been warming Earth above the freezing point but would threaten to boil the seas under a warmer sun.

Control of carbon dioxide would be just one of many loops through which climate is still controlled by and for the biosphere, according to the Gaia hypothesis. There would be more webs of feedbacks controlling the composition of seawater, so that it would not become too salty, and the composition of the atmosphere, so that its content of oxygen, among a number of gases, would remain within an optimal range.

Gaia had been largely ignored by mainstream scientists for almost 20 years, but it started taking some hard knocks soon after Lovelock's engaging introductory talk Monday morning. However, by the discussion period Monday afternoon Lovelock had already retracted what became known as the strong version of the Gaia hypothesis.

Well into this first discussion, someone sensed confusion as to what exactly was being debated and asked for a statement of the hypothesis. The Gaia hypothesis, Lovelock replied, holds "that the nonliving and living represent a self-regulating system that keeps itself in a constant state," or at least within a limited range of conditions. But you said nothing about homeostasis by and *for* the biosphere, his questioner noted. Lovelock agreed. "Our thoughts have evolved over the last 20 years," he said. "In the early stages one tended to speak poetically. I hope that we are now speaking more scientifically."

Without life, would Earth's climate be wildly out of control?, asked James Kasting of the National Aeronautics and Space Administration's Ames Research Center. Yes, it would be, replied Lovelock. Lynn Margulis of Boston University, the staunchest American proponent of Gaia, concurred. Are extinction crises, in which 50 or 70% of species disappear, within the limits of Gaia? "Well within," said Lovelock, "the persistence of life shows that."

Even as the new Gaia hypothesis was emerging, James Kirchner and John Harte of the University of California at Berkeley, speaking at the Tuesday night session on epistemology, were destroying the old Gaia and calling into question the whole range of Gaia hypotheses. The traditional, teleological, strong hypothesis is simply not testable, they said, while the weaker forms, in which life merely influences the environment, are so obviously correct that they do not merit status as hypotheses.

Lovelock conceded immediately that the strong Gaia must be abandoned. Kirchner's analysis was "a clear-cut demolition of Gaia," he said. "I'm an inventor, one more intuitive than rational. Being an inventor, it's been very hard to explain what I want to. Most of [Kirchner's] criticisms are of what we said a long time ago. We've been at this for 20 years."

In an informal session the next day during a break, Kirchner attacked that defense as true but inadequate, saying that "you've changed, but your old ideas are still out there. There are people who still think you mean what you said. If you came out in print and said you don't mean that any-more, we might get somewhere."

It may not be in print yet, but the current Lovelock-Margulis version of the Gaia hypothesis would seem to hold that life has controlled its environment within limits narrow enough that life continued. This is a "homeostatic Gaia," in Kirchner's terms, devoid of purposefulness but still powerful.

A vocal contingent of mainstream researchers at the meeting denied that there is any evidence of or even need for such a homeostatic Gaia; simple, mindless chemistry and physics can suffice. A central focus of this debate was the control of atmospheric carbon dioxide, a trace gas that plays a major role in Earth's greenhouse.

Carbon dioxide was probably not always such a minor component of the atmosphere. In Earth's youth the planet was in dire need of a blanket of carbon dioxide, perhaps a thousand times heavier than the present one, to hold in the warmth of the feeble sun that shone then. During the solar system's first 2 billion years, Earth would have been frozen over without a strong carbon dioxide greenhouse; at present, such a greenhouse would leave Earth a steamy inferno. That is the paradox of the faint young sun.

What Earth needed was not only an early source of warmth but also a way of gradually turning down that warmth in response to the brightening of the sun. Advocates of Gaia have pointed to the seemingly aggressive way the biosphere participates today in the cycling of carbon dioxide—depositing great masses of calcium carbonate shells as limestone and breaking down the very rocks. Surely, they argued, such a biosphere must control atmospheric carbon dioxide.

No, answered the geophysicists at the meeting, a mechanism involving material as inanimate as rock and water could make it work. According to a mechanism suggested by James Walker and Paul Hays of the University of Michigan and Kasting, a cycling of carbon dioxide involving the motion of tectonic plates and the dissolution of rock by acidified water could have maintained habitable conditions as the sun brightened. At one end of the cycle, plate tectonics would have kept Earth's share of carbon dioxide from being entirely locked up as calcium carbonate deposits; no control mechanism could exist if there were no carbon dioxide gas to work with. But in a world of drifting and sinking plates like Earth, a limestone deposit need not be the end of the line. Calcium carbonate deposits can be carried down toward the hot mantle with the plates as they sink into deep-sea trenches. There some of the carbon dioxide is cooked out of carbonate rocks and returned to the atmosphere through volcanoes.

The other end of the cycle provides the feedback mechanism, the thermostat in this case. Atmospheric carbon dioxide dissolves in rainwater, forms carbonic acid, and dissolves calcium-containing silicate rock. The freed calcium and neutralized acid is lost to the sea. This is chemical weathering. If the temperature rises for any reason, chemical weathering accelerates, but ocean water also evaporates faster, and the rain falls faster. The more rain, the more carbon dioxide is removed to be lost through even faster weathering. With carbon dioxide decreasing, the temperature rise is countered. A temperature drop has the opposite effect, slowing the removal of carbon dioxide, which allows volcanoes to increase atmospheric carbon dioxide and thus temperature.

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This negative feedback between temperature and atmospheric carbon dioxide—whether temperature goes up or down carbon dioxide counters the change—can operate in the absence of life. Those inclined toward Gaian mechanisms pointed out that plants greatly accelerate the rate of weathering and thus the removal of carbon dioxide. Plants do this by increasing soil concentrations of carbon dioxide up to 40 times over that now in the atmosphere. Perhaps that could provide a useful feedback, it was argued.

Tyler Volk of New York University constructed a global model with such a feedback in it. It includes plants in its chemical weathering because they not only lead to carbon dioxide in the soil, but they also respond to changes in atmospheric carbon dioxide, which makes for a feedback loop. Volk found that a doubling of plant productivity under increased carbon dioxide could lead to a cooling of 1°C. There being practical limits on plant productivity, he noted, this feedback could be significant but not dominant.

That is the way much of the week went—the "Earth is alive" camp, the principals being Lovelock, Margulis, and Andrew Watson of the Marine Biological Association's laboratory at Plymouth, England, suggesting that life's obvious influence on its surroundings must extend to control as well, while the geochemists insisted that they have found no need to invoke life as a dominant force. Even in the case of oxygen, which is solely a product of photosynthesis, control resides in a balance of inorganic processes, according to this thinking.

Kasting and Heinrich Holland of Harvard University summed up the anti-Gaia sentiment in a joint statement of their own: "The biosphere is one of several factors that affect the composition of the ocean and atmosphere. Its effects are more important in some cases than others, but there is no compelling reason to suppose that the biosphere controls the whole system." By this thinking, life has done so well against so many obstacles because it readily adapts to conditions as it finds them, not because it exerts control over them.

Gaia, even in its more modest guise, may have failed to entice the geochemists, but a number of researchers expressed some empathy for the concept, especially those dealing with the trace gases of the atmosphere. In the trace gas discussion period, Ralph Cicerone, a prominent researcher from the National Center for Atmospheric Research (NCAR) in Boulder, commented that "I've been stimulated so much by Lovelock's and Margulis's work the past 10 years."

One of Cicerone's interests has been methane. Seventy percent of the methane produced comes from microorganisms. It is a greenhouse gas, and through the web of reactions linking atmospheric trace chemicals it influences a variety of processes, from pollutant removal and stratospheric ozone destruction to the fate of oxygen. The possibilities for life-nonlife interactions are obviously numerous.

Another area where "the Gaian view raises some interesting questions," Cicerone said, is atmospheric nitrogen. If chemistry had its way, that gas would be transformed to nitrate dissolved in the ocean, its most stable state, leaving Earth with precious little atmospheric pressure. Denitrifying bacteria return nitrate-nitrogen to its gaseous state, saving the day in the Gaian view, but Cicerone is as yet unsure whether that is the whole story.

Another trace gas chemist admitting to some Gaian thinking was Peter Liss of the University of East Anglia. Lovelock "is the stimulus of many of the measurements that my group has made," he noted. Liss's current interest is dimethylsulfide or DMS.

The recognition of DMS as the geochemical link in a possible feedback loop between life in the sea and climate is probably the most respectable and most promising product of the Gaian approach to understanding Earth. The story of DMS illustrates what Gaia, even as an overstatement, has done best—stimulate productive offbeat thinking and cross-discipline contacts.

Lovelock started things off when he took his latest invention to sea in 1971 in search of DMS. His electron-capture detector, now in wide use in everything from pesticide-analyzing gas chromatographs to explosives-sniffing bomb detectors, is an exquisitely sensitive tool for studying DMS. Lovelock and his colleagues suspected DMS produced by phytoplankton was the missing marine source of sulfur for the land. He found the DMS in seawater, which was later found to be ubiquitous by Meinrat Andreae of the Max Planck Institute in Mainz. But what was it doing in the middle of the ocean? By Gaian thinking it presumably has a larger purpose.

Lovelock was stymied until 1984 when he visited the University of Washington to give a talk. He remarked to Robert Charlson, a specialist in atmospheric particles and cloud physics, that "your colleagues are giving me a hard time because I have no mechanism" for linking DMS and the sulfate aerosol that it forms in the atmosphere to climate.

Charlson confirmed that the aerosol alone would not suffice, but he came up with an amplifier that would make it work. The submicrometer aerosol could form cloud droplets that are 100 times larger than the original aerosol and thus influence the reflectivity of marine clouds. The more reflective the clouds, the cooler the surface, which could close the loop by affecting the production of DMS (see box).

The four principals now involved—Charlson, Lovelock, Andreae, and Stephen Warren, also at the University of Washington—then published a paper proposing that the DMS-climate link has tended to cool Earth, perhaps against the brightening sun or increasing greenhouse. If DMS production were to cease, Earth might warm by several degrees, they said. But among their assumptions was one that the reflectivity of marine clouds is sensitive enough to changes in the number of fine aerosol particles that can form cloud droplets. Calculations indicted that it was, but Charlson was suggesting in his talks that it should be demonstrated experimentally by adding DMS or aerosol particles to marine air and looking for changes in cloud reflectivity.

At one talk, James Coakley of NCAR stood to say that the experiment had already been done, with positive results. Satellite images had revealed long plumes of cloud intensified by the addition of smoke particles from ship stacks. Marine clouds can become brighter if they have more particles.

The ripples from Lovelock's 1971 detection of DMS are still spreading. Several meeting attendees made intentionally vague mention of a forthcoming paper by Michel Legrand and Robert Delmas of the Laboratory of Glaciology and Geophysics of the Environment in Grenoble. They reportedly have found a record of a DMS proxy, methylsulfonic acid, in an Antarctic ice core that indicates above-average production during the most recent ice age, at least near Antarctica. If true, this feedback loop would seem to enhance ice ages. Lovelock suggested with a smile that Gaia might thus prefer a cooler climate than the present one.

The DMS-climate link has some hurdles to surmount. Most important will be sorting out the nature of the so-called "Gaian switch," if any, connecting changes in solar radiation reaching the surface and changes in the production of DMS. The direction, much less the magnitude, of the change is totally unknown. But the great attraction of this proposed feedback is its testability. Identifying testable Gaian hypotheses, which have been in painfully short supply, was the primary purpose of the meeting. Now that Gaia has been cloaked in more fashionable garb, there should be more testable links between the living and the nonliving worlds. ■ Richard A. Kerr

ADDITIONAL READING

R. Charlson, J. Lovelock, M. Andreae, S. Warren, "Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate," *Nature* **326**, 655 (1987).

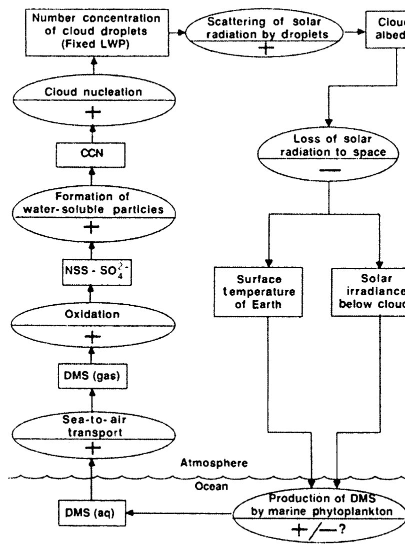
J. Kasting, O. Toon, J. Pollack, "How climate evolved on the terrestrial planets," *Sci. Am.* **258**, 90 (Feb. 1988).

L. Lovelock, *Gaia: A New Look at Life on Earth* (Oxford Univ. Press, Oxford, 1979; reprinted with a new preface, 1987).

A Loop Between Plant and Cloud

The Gaia-like feedback loop proposed by Robert Charlson and his colleagues would link the microscopic phytoplankton living near the sea surface and the reflectivity of stratus clouds and thus climate. To follow the loop around:

■ Assume first that for some reason the production of dimethylsulfide (DMS) by phytoplankton increases. Perhaps a cooling climate favors species that are copious DMS producers. DMS is actually a breakdown product of a compound that helps balance the osmotic pressure felt by phytoplankton in seawater.



R. Charlson et al., *Nature*

■ Increased DMS in seawater would lead fairly straightforwardly to more DMS gas in the atmosphere and through oxidation more water-soluble sulfate particles smaller than 1 micrometer in size. (The plus and minus signs indicate the effect of a positive change in the preceding box on the subsequent box.) These particles can serve as centers for the condensation of water to form cloud droplets. Cloud droplets cannot form below a relative humidity of about 300% without these nuclei.

■ A higher concentration of cloud condensation nuclei would lead to a higher concentration of cloud droplets. Marine air is so clean, having only a few hundred of these particles per cubic centimeter, that the number of cloud droplets is limited by the supply of condensation nuclei. With the increased number of condensation nuclei, the same amount of water would be spread around more but smaller droplets.

■ More but smaller cloud droplets would lead to more solar radiation being reflected away from the surface back to space. This is where the amplification enters.

■ The increased loss of radiation to space would both cool the ocean surface and decrease the solar energy available for photosynthesis, and there is the rub. No one knows how DMS production would respond. Would DMS producers flourish in the cooler climate and cool it still more, or would they dwindle under less light and thus act as a thermostat to counter the cooling trend? Characterizing this "Gaian switch" seems to be the toughest part of deciphering the global influence of life on its environment. ■ R.A.K.