

Lovelock, J. 1979

CHAPTER 1

Introductory

Gaia: a new look at  
life on earth

As I write, two Viking spacecraft are circling our fellow planet Mars, awaiting landfall instructions from the Earth. Their mission is to search for life, or evidence of life, now or long ago. This book also is about a search for life, and the quest for Gaia is an attempt to find the largest living creature on Earth. Our journey may reveal no more than the almost infinite variety of living forms which have proliferated over the Earth's surface under the transparent case of the air and which constitute the biosphere. But if Gaia does exist, then we may find ourselves and all other living things to be parts and partners of a vast being who in her entirety has the power to maintain our planet as a fit and comfortable habitat for life.

The quest for Gaia began more than fifteen years ago, when NASA (the National Aeronautics and Space Administration of the USA) first made plans to look for life on Mars. It is therefore right and proper that this book should open with a tribute to the fantastic Martian voyage of those two mechanical Norsemen.

In the early nineteen-sixties I often visited the Jet Propulsion Laboratories of the California Institute of Technology in Pasadena, as consultant to a team, later to be led by that most able of space biologists Norman Horowitz, whose main objective was to devise ways and means of detecting life on Mars and other planets. Although my particular brief was to advise on some comparatively simple problems of instrument design, as one whose childhood was illuminated by the writings of Jules Verne and Olaf Stapledon I was delighted to have the chance of discussing at first hand the plans for investigating Mars.

At that time, the planning of experiments was mostly based on the assumption that evidence for life on Mars would be

much the same as for life on Earth. Thus one proposed series of experiments involved dispatching what was, in effect, an automated microbiological laboratory to sample the Martian soil and judge its suitability to support bacteria, fungi, or other micro-organisms. Additional soil experiments were designed to test for chemicals whose presence would indicate life at work: proteins, amino-acids, and particularly optically active substances with the capacity that organic matter has to twist a beam of polarized light in a counter-clockwise direction.

After a year or so, and perhaps because I was not directly involved, the euphoria arising from my association with this enthralling problem began to subside, and I found myself asking some rather down-to-earth questions, such as, 'How can we be sure that the Martian way of life, if any, will reveal itself to tests based on Earth's life style?' To say nothing of more difficult questions, such as, 'What is life, and how should it be recognized?'

Some of my still sanguine colleagues at the Jet Propulsion Laboratories mistook my growing scepticism for cynical disillusion and quite properly asked, 'Well, what would you do instead?' At that time I could only reply vaguely, 'I'd look for an entropy reduction, since this must be a general characteristic of all forms of life.' Understandably, this reply was taken to be at the best unpractical and at worst plain obfuscation, for few physical concepts can have caused as much confusion and misunderstanding as has that of entropy.

It is almost a synonym for disorder and yet, as a measure of the rate of dissipation of a system's thermal energy, it can be precisely expressed in mathematical terms. It has been the bane of generations of students and is direfully associated in many minds with decline and decay, since its expression in the Second Law of Thermodynamics (indicating that all energy will eventually dissipate into heat universally distributed and will no longer be available for the performance of useful work) implies the predestined and inevitable run-down and death of the Universe.

Although my tentative suggestion had been rejected, the idea of looking for a reduction or reversal of entropy as a sign of life had implanted itself in my mind. It grew and waxed

fruitful until, with the help of many colleagues, Dian Hitchcock, Sidney Epton, Peter Simmonds, and especially Lynn Margulis, it evolved into the hypothesis which is the subject of this book.

Back home in the quiet countryside of Wiltshire, after my visits to the Jet Propulsion Laboratories, I had time to do more thinking and reading about the real character of life and how one might recognize it anywhere and in any guise. I expected to discover somewhere in the scientific literature a comprehensive definition of life as a physical process, on which one could base the design of life-detection experiments, but I was surprised to find how little had been written about the nature of life itself. The present interest in ecology and the application of systems analysis to biology had barely begun and there was still in those days the dusty academic air of the classroom about the life sciences. Data galore had been accumulated on every conceivable aspect of living species, from their outermost to their innermost parts, but in the whole vast encyclopaedia of facts the crux of the matter, life itself, was almost totally ignored. At best, the literature read like a collection of expert reports, as if a group of scientists from another world had taken a television receiver home with them and had reported on it. The chemist said it was made of wood, glass, and metal. The physicist said it radiated heat and light. The engineer said the supporting wheels were too small and in the wrong place for it to run smoothly on a flat surface. But nobody said what it was.

This seeming conspiracy of silence may have been due in part to the division of science into separate disciplines, with each specialist assuming that someone else has done the job. Some biologists may believe that the process of life is adequately described by some mathematical theorem of physics or cybernetics, and some physicists may assume that it is factually described in the recondite writings on molecular biology which one day he will find time to read. But the most probable cause of our closed minds on the subject is that we already have a very rapid, highly efficient life-recognition programme in our inherited set of instincts, our read-only memory as it might be called in computer technology. Our recognition of living

things, both animal and vegetable, is instant and automatic, and our fellow-creatures in the animal world appear to have the same facility. This powerful and effective but unconscious process of recognition no doubt originally evolved as a survival factor. Anything living may be edible, lethal, friendly, aggressive, or a potential mate, all questions of prime significance for our welfare and continued existence. However, our automatic recognition system appears to have paralysed our capacity for conscious thought about a definition of life. For why should we need to define what is obvious and unmistakable in all its manifestations, thanks to our built-in programme? Perhaps for that very reason, it is an automatic process operating without conscious understanding, like the autopilot of an aircraft.

Even the new science of cybernetics has not tackled the problem, although it is concerned with the mode of operation of all manner of systems from the simplicity of a valve-operated water tank to the complex visual control process which enables your eyes to scan this page. Much, indeed, has already been said and written about the cybernetics of artificial intelligence, but the question of defining real life in cybernetic terms remains unanswered and is seldom discussed.

During the present century a few physicists have tried to define life. Bernal, Schroedinger, and Wigner all came to the same general conclusion, that life is a member of the class of phenomena which are open or continuous systems able to decrease their internal entropy at the expense of substances or free energy taken in from the environment and subsequently rejected in a degraded form. This definition is not only difficult to grasp but is far too general to apply to the specific detection of life. A rough paraphrase might be that life is one of those processes which are found whenever there is an abundant flow of energy. It is characterized by a tendency to shape or form itself as it consumes, but to do so it must always excrete low-grade products to the surroundings.

We can now see that this definition would apply equally well to eddies in a flowing stream, to hurricanes, to flames, or even to refrigerators and many other man-made contrivances. A flame assumes a characteristic shape as it burns, and needs an adequate supply of fuel and air to keep going, and we are now

only too well aware that the pleasant warmth and dancing flames of an open fire have to be paid for in the excretion of waste heat and pollutant gases. Entropy is reduced locally by the flame formation, but the overall total of entropy is increased during the fuel consumption.

Yet even if too broad and vague, this classification of life at least points us in the right direction. It suggests, for example, that there is a boundary, or interface, between the 'factory' area where the flow of energy or raw materials is put to work and entropy is consequently reduced, and the surrounding environment which receives the discarded waste products. It also suggests that life-like processes require a flux of energy above some minimal value in order to get going and keep going. The nineteenth-century physicist Reynolds observed that turbulent eddies in gases and liquids could only form if the rate of flow was above some critical value in relation to local conditions. The Reynolds dimensionless number can be calculated from simple knowledge of a fluid's properties and its local flow boundaries. Similarly, for life to begin, not only the quantity but also the quality, or potential, of the energy flow must be sufficient. If, for example, the sun's surface temperature were 500 degrees instead of 5,000 degrees Centigrade and the Earth were correspondingly closer, so that we received the same amount of warmth, there would be little difference in climate, but life would never have got going. Life needs energy potent enough to sever chemical bonds; mere warmth is not enough.

It might be a step forward if we could establish dimensionless numbers like the Reynolds scale to characterize the energy conditions of a planet. Then those enjoying, with the Earth, a flux of free solar energy above these critical values would predictably have life whilst those low on the scale, like the cold outer planets, would not.

The design of a universal life-detection experiment based on entropy reduction seemed at this time to be a somewhat unpromising exercise. However, assuming that life on any planet would be bound to use the fluid media—oceans, atmosphere, or both—as conveyor-belts for raw materials and waste products, it occurred to me that some of the activity associated

with concentrated entropy reduction within a living system might spill over into the conveyor-belt regions and alter their composition. The atmosphere of a life-bearing planet would thus become recognizably different from that of a dead planet.

Mars has no oceans. If life had established itself there, it would have had to make use of the atmosphere or stagnate. Mars therefore seemed a suitable planet for a life-detection exercise based on chemical analysis of the atmosphere. Moreover, this could be carried out regardless of the choice of landing site. Most life-detection experiments are effective only within a suitable target area. Even on Earth, local search techniques would be unlikely to yield much positive evidence of life if the landfall occurred on the Antarctic ice sheet or the Sahara desert or in the middle of a salt lake.

While I was thinking on these lines, Dian Hitchcock visited the Jet Propulsion Laboratories. Her task was to compare and evaluate the logic and information-potential of the many suggestions for detecting life on Mars. The notion of life detection by atmospheric analysis appealed to her, and we began developing the idea together. Using our own planet as a model, we examined the extent to which simple knowledge of the chemical composition of the Earth's atmosphere, when coupled with such readily accessible information as the degree of solar radiation and the presence of oceans as well as land masses on the Earth's surface, could provide evidence for life.

Our results convinced us that the only feasible explanation of the Earth's highly improbable atmosphere was that it was being manipulated on a day-to-day basis from the surface, and that the manipulator was life itself. The significant decrease in entropy—or, as a chemist would put it, the persistent state of disequilibrium among the atmospheric gases—was on its own clear proof of life's activity. Take, for example, the simultaneous presence of methane and oxygen in our atmosphere. In sunlight, these two gases react chemically to give carbon dioxide and water vapour. The rate of this reaction is such that to sustain the amount of methane always present in the air, at least 1,000 million tons of this gas must be introduced into the atmosphere yearly. In addition, there must be some means of replacing the oxygen used up in oxidizing methane and this

requires a production of at least twice as much oxygen as methane. The quantities of both of these gases required to keep the Earth's extraordinary atmospheric mixture constant was improbable on an abiological basis by at least 100 orders of magnitude.

Here, in one comparatively simple test, was convincing evidence for life on Earth, evidence moreover which could be picked up by an infra-red telescope sited as far away as Mars. The same argument applies to other atmospheric gases, especially to the ensemble of reactive gases constituting the atmosphere as a whole. The presence of nitrous oxide and of ammonia is as anomalous as that of methane in our oxidizing atmosphere. Even nitrogen in gaseous form is out of place, for with the Earth's abundant and neutral oceans, we should expect to find this element in the chemically stable form of the nitrate ion dissolved in the sea.

Our findings and conclusions were, of course, very much out of step with conventional geochemical wisdom in the sixties. With some exceptions, notably Rubey, Hutchinson, Bates, and Nicolet, most geochemists regarded the atmosphere as an end-product of planetary outgassing and held that subsequent reactions by abiological processes had determined its present state. Oxygen, for example, was thought to come solely from the breakdown of water vapour and the escape of hydrogen into space, leaving an excess of oxygen behind. Life merely borrowed gases from the atmosphere and returned them unchanged. Our contrasting view required ~~an atmosphere which was a dynamic extension of the biosphere itself~~. It was not easy to find a journal prepared to publish so radical a notion but, after several rejections, we found an editor, Carl Sagan, prepared to publish it in his journal, *Icarus*.

Nevertheless, 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. To make matters worse, in September 1965 the US

Congress decided to abandon the first Martian exploration programme, then called Voyager. For the next year or so, ideas about looking for life on other planets were to be discouraged.

Space exploration has always served as a convenient whipping-boy to those needing money for some worthy cause, yet it is far less expensive than many a stuck-in-the-mud, down-to-earth technological failure. Unfortunately, the apologists for space science always seem over-impressed by engineering trivia and make far too much of non-stick frying pans and perfect ball-bearings. To my mind, the outstanding spin-off from space research is not new technology. The real bonus has been that for the first time in human history we have had a chance to look at the Earth from space, and the information gained from seeing from the outside our azure-green planet in all its global beauty has given rise to a whole new set of questions and answers. Similarly, thinking about life on Mars gave some of us a fresh standpoint from which to consider life on Earth and led us to formulate a new, or perhaps revive a very ancient, concept of the relationship between the Earth and its biosphere.

By great good fortune, so far as I was concerned, the nadir of the space programme coincided with an invitation from Shell Research Limited for me to consider the possible global consequences of air pollution from such causes as the ever-increasing rate of combustion of fossil fuels. This was in 1966, three years before the formation of Friends of the Earth and similar pressure-groups brought pollution problems to the forefront of the public mind.

Like artists, independent scientists need sponsors but this rarely involves a possessive relationship. Freedom of thought is the rule. This should hardly need saying, but nowadays many otherwise intelligent individuals are conditioned to believe that all research work supported by a multi-national corporation must be suspect by origin. Others are just as convinced that similar work coming from an institution in a Communist country will have been subject to Marxist theoretical constraint and will therefore be diminished. The ideas and opinions expressed in this book are inevitably influenced to some degree by the society in which I live and work, and

especially by close contact with numerous scientific colleagues in the West. So far as I know, these mild pressures are the only ones which have been exerted on me.

The link between my involvement in problems of global air pollution and my previous work on life detection by atmospheric analysis was, of course, the idea that the atmosphere might be an extension of the biosphere. It seemed to me that any attempt to understand the consequences of air pollution would be incomplete and probably ineffectual if the possibility of a response or an adaptation by the biosphere was overlooked. The effects of poison on a man are greatly modified by his capacity to metabolize or excrete it; and the effect of loading a biospherically controlled atmosphere with the products of fossil fuel combustion might be very different from the effect on a passive inorganic atmosphere. Adaptive changes might take place which would lessen the perturbations due, for instance, to the accumulation of carbon dioxide. Or the perturbations might trigger some compensatory change, perhaps in the climate, which would be good for the biosphere as a whole but bad for man as a species.

Working in a new intellectual environment, I was able to forget Mars and to concentrate on the Earth and the nature of its atmosphere. The result of this more single-minded approach was the development of the hypothesis that the entire range of living matter on Earth, from whales to viruses, and from oaks to algae, could be regarded as constituting a single living entity, capable of manipulating the Earth's atmosphere to suit its overall needs and endowed with faculties and powers far beyond those of its constituent parts.

It is a long way from a plausible life-detection experiment to the hypothesis that the Earth's atmosphere is actively maintained and regulated by life on the surface, that is, by the biosphere. Much of this book deals with more recent evidence in support of this view. In 1967 the reasons for making the hypothetical stride were briefly these:

- Life first appeared on the Earth about 3,500 million years ago. From that time until now, the presence of fossils shows that the Earth's climate has changed very little. Yet the

output of heat from the sun, the surface properties of the Earth, and the composition of the atmosphere have almost certainly varied greatly over the same period.

The chemical composition of the atmosphere bears no relation to the expectations of steady-state chemical equilibrium. The presence of methane, nitrous oxide, and even nitrogen in our present oxidizing atmosphere represents violation of the rules of chemistry to be measured in tens of orders of magnitude. Disequilibrium on this scale suggest that the atmosphere is not merely a biological product, but more probably a biological construction: not living, but like a cat's fur, a bird's feathers, or the paper of a wasp's nest, an extension of a living system designed to maintain a chosen environment. Thus the atmospheric concentration of gases such as oxygen and ammonia is found to be kept at an optimum value from which even small departures could have disastrous consequences for life.

The climate and the chemical properties of the Earth now and throughout its history seem always to have been optimal for life. For this to have happened by chance is as unlikely as to survive unscathed a drive blindfold through rush-hour traffic.

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 Biocymbetic Universal System Tendency/Homoeostasis. 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.

I first put forward the Gaia hypothesis at a scientific meeting about the origins of life on Earth which took place in Princeton, New Jersey, in 1969. Perhaps it was poorly presented. It certainly did not appeal to anyone except Lars Gunnar Sillen, the Swedish chemist now sadly dead, and Lynn Margulis, of Boston University, who had the task of editing our various contributions. A year later in Boston, Lynn and I met again and began a most rewarding collaboration which, with her deep knowledge and insight as a life scientist, was to go far in adding substance to the wraith of Gaia, and which still happily continues.

We have since defined Gaia as a complex entity involving the Earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet. The maintenance of relatively constant conditions by active control may be conveniently described by the term 'homoeostasis'.

Gaia has remained a hypothesis but, like other useful hypotheses, she has already proved her theoretical value, if not her existence, by giving rise to experimental questions and answers which were profitable exercises in themselves. If, for example, the atmosphere is, among other things, a device for conveying raw materials to and from the biosphere, it would be reasonable to assume the presence of carrier compounds for elements essential in all biological systems, for example, iodine and sulphur. It was rewarding to find evidence that both were conveyed from the oceans, where they are abundant, through the air to the land surface, where they are in short supply. The carrier compounds, methyl iodide and dimethyl sulphide respectively, are directly produced by marine life. Scientific curiosity being unquenchable, the presence of these interesting compounds in the atmosphere would no doubt have been discovered in the end and their importance discussed without the stimulus of the Gaia hypothesis. But they were actively sought as a result of the hypothesis and their presence was consistent with it.

If Gaia exists, the relationship between her and man, a dominant animal species in the complex living system, and the possibly shifting balance of power between them, are questions of obvious importance. I have discussed them in later chapters, but this book is written primarily to stimulate and entertain. The Gaia hypothesis is for those who like to walk or simply stand and stare, to wonder about the Earth and the life it bears, and to speculate about the consequences of our own presence here. It is an alternative to that pessimistic view which sees nature as a primitive force to be subdued and conquered. It is also an alternative to that equally depressing picture of our planet as a demented spaceship, forever traveling, driverless and purposeless, around an inner circle of the sun.