Gaia

A New look at Life on Earth

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One of his many inventions was the electron capture detector, which was important in the detection and measurement of CFCs in the atmosphere. He worked with NASA and some of his inventions were adopted in their programme of planetary exploration. His other books include *The Ages of Gaia* and *Homage to Gaia* (also published by Oxford University Press) and *Gaia: The Practical Science of Planetary Medicine*.

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Preface

Twenty–six years ago when I first started writing this book, I had no clear idea of what Gaia was although I had thought deeply about her. What I did know was that the Earth was different from Mars and Venus. It was a planet with apparently the strange property of keeping itself always a fit and comfortable place for living things to inhabit. I had the idea that somehow this property was not an accident of its position in the Solar System but was a consequence of life on its surface. The word 'Gaia' came from my friend and near neighbour, the novelist William Golding. He thought that such an idea should be named Gaia after the Greek goddess of the Earth.

In those days of the early 1970s, we were still innocent about the environment. Rachel Carson had given us cause to worry, farmers were destroying the pleasant countryside we knew by the overuse of chemicals but it all still seemed all right. Global change, biodiversity, the ozone layer, and acid rain all were ideas barely visible in science itself, still less of public concern. We were all to some extent participants in the cold war and far more of our time went into serving in that war than we ever realized. As a scientist involved with NASA's planetary exploration programme I was only dimly aware that the lift vehicles that took our experiments to Mars and beyond would never have been mad for pure science alone. We were riding the war horses of the silent war between the Soviet Union and the United States. The navigation system that faultlessly found its way to a chosen destination on Mars could also have precisely enabled the demolition of an enemy missile battery.

The cold war distorted much more than space science. To my mind, the most serious damage don was to our understanding of our own planet. We were naturally fearful of the consequences of a hot war fought with nuclear weapons and knew that at the least it would destroy the civilizations of the combatants. These real fears led to the growth in the West of the Campaign for Nuclear Disarmamen (CND) and it became the first international environmental movement. So pressing were our anxieties over the consequences of nuclear war that at times it seemed that nuclear radiation was the quintessence of our fears. The dangers of habitat destruction and the inflation of the air with greenhouse gases seemed remote and trivial concerns in the 1970s and 1980s, especially to those campaigning for the abolition of everything nuclear.

When the cold war fizzled out in the last years of the century we had an environmental movemen which included active members who came from the old CND and they were still mainly fighting the industrial and military systems of the West that sustained nuclear weapons. It was easy for them to transfer their campaign to attacking all science-based large companies of the First World especially where there was a link, however tenuous, with a threat to humanity.

I consider this politicization of Green thought and action has led us dangerously astray. It stops u from realizing that it is not them, the multinational companies or the state industries of Russia and China that are wholly to blame for our fast degrading world. Our much too vociferous advocates, the consumer lobbies, and we the consumers are equally responsible for the gaseous greenhouse and the extinction of wildlife. The multinational companies would not exist if we had not demanded their products and at a price that forces them to produce without enough care for the consequences. In our belief that all that matters is the good of humankind we foolishly forget how much we depend upon a the other living things on Earth.

We need to love and respect the Earth with the same intensity that we give to our families and ou tribe~~. It is not a political matter of them and us or some adversarial affair with lawyers involved~~; our contract with the Earth is fundamental, for we are a part of it and cannot survive without a healthy planet as our home. I wrote this book when we were only just beginning to glimpse the true nature of our planet and I wrote it as a story of discovery. If you are someone wanting to know for the first tim about the idea of Gaia, it is the story of a planet that is alive in the same way that a gene is selfish.

This book is the story of Gaia, about getting to know her without understanding what she is. Now twenty-six years on, I know her better and see that in this first book I made mistakes. Some were serious, such as the idea that the Earth was kept comfortable by and for its inhabitants, the living organisms. I failed to make clear that it was not the biosphere alone that did the regulating but the whole thing, life, the air, the oceans, and the rocks. The entire surface of the Earth including life is a self–regulating entity and this is what I mean by Gaia. I was also foolish to suggest that we could warm the Earth in the event of an imminent ice age by deliberately releasing chlorofluorocarbons int the air, exploiting their potent greenhouse effect to keep us warm. In those days of innocence, the technological fix was respectable. I have not altered the original text to correct any of these mistakes although a parenthetic correction follows these errors. The story is as it was and lets you see how the idea of Gaia developed, not only in science, but also as part of thought on a wider scale. I never imagined in 1974 just how wide this might be.

When I started to write in 1974 in the unspoilt landscape of Western Ireland, it was like living in house run by Gaia, someone who tried hard to make all her guests comfortable. I began more and more to see things through her eyes and slowly dropped off, like an old coat, my loyalty to the humanist Christian belief in the good of mankind as the only thing that mattered. I began to see us al as part of the community of living things that unconsciously keep the Earth a comfortable home, and that we humans have no special rights only obligations to the community of Gaia.

On 4 July 1994, the United States of America awarded the Liberty Medal to the Czech president Václav Havel. The title of his speech of acceptance was, ‘We are not alone nor for ourselves alone’. He recognized that the Modern age has ended, the artificial world order of the past decades has collapsed and a new more just order has not yet emerged. He went on to say that we are now where classically modern solutions do not give a satisfactory response. We need to anchor the idea of huma rights and freedoms in a different place and in a different way than has been done so far. Paradoxically, he said, inspiration for the renewal of this lost integrity can again be found in science. In a science that is new—post modern—a science producing ideas that in a certain sense allow it to transcend its own limits. He gave two examples: first, the anthropic cosmological principle where science finds itself on the border with myth which returns us to an ancient idea, namely, that we are not just an accidental anomaly. Second, the Gaia theory in which all life and all the material parts of the Earth’s surface make up a single system, a kind of mega–organism, and a living planet. In Havel’ words, ‘According to the Gaia Hypothesis, we are parts of a greater whole. Our destiny is not dependent merely on what we do for ourselves but also on what we do for Gaia as a whole. If we endanger her, she will dispense with us in the interests of a higher value—life itself.’ The statesman Havel’s acceptance that human rights are not enough is timely and not only for ourselves as humans but also for Gaia. She was first expressed in this book at a time when the science of Gaia was no mor than the noticing of a stable planet made of unstable parts. Something wholly unexpected, something improbable, as it must have seemed when the world was first found round, not flat; how Gaia worked was still ten years from discovery. Because of my ignorance twenty–six years ago, I wrote as a storyteller and gave poetry and myth their place along with science. In the preface of the first edition I warned:

Occasionally it is difficult, without excessive circumlocution, to avoid talking of Gaia as if she were ~~known to be sentient. This is meant no more seriously than is the appellation ‘she’ when given~~ to a ship by those who sail in her, as a recognition that even pieces of wood and metal when specifically designed and assembled may achieve a composite identity with its own characteristic signature, as distinct from being the mere sum of its parts.

Most of the criticism of Gaia has come from scientists who read the first edition of this book. None o them appeared to notice the disclaimer, nor did they read the ten or so papers on Gaia in peer–reviewed scientific journals. The critics took their science earnestly and to them mere association wi myth and storytelling made it bad science. My disclaimer was about as much use as is the health warning on a packet of cigarettes to a nicotine addict.

The force of their objections slowed the natural development of Gaia theory. Until 1995 it was nearly impossible for a scientist anywhere to publish a paper on Gaia, unless to disprove or disparage it; now at last it is a candidate theory awaiting approval. Unfortunately for me, the way forward splits at a cruel bifurcation. To establish Gaia as a fact I must take the first path, that of science. As a guide on the best way to live with the Earth, it will only be believed if it comes with majority support from the scientific community—politicians and governmental agencies dare not act on myth—and demand scientific approval. To keep Gaia as something we all can understand I must take the second path, the one that goes to the postmodern world. Here science itself is questioned, but the Gaia of this book is acceptable even to statesmen and states–women. Which of these paths should I take?

I have tried for them both by rewriting my second book, *The Ages of Gaia*, so that it is specificall for scientists, and leaving this book as it was. If I were to rewrite this first book in scientifically correct language, and make it esoteric, it would be incomprehensible. It would be opaque not only to non–scientists, but to engineers, physicians, and practical environmentalists who need moral guidanc as well as technology within their work. The few alterations I have made to this book are to correct facts of science that were wrong, such as that the release of methane to the air is 500, not 1,000, million tons a year, as was thought by scientists twenty–six years ago. I have tried to define that vagu word ‘biosphere’. Originally, it was a precise geographical term defining the region of the Earth whe living organisms existed. Gradually, it lost precision and became a vogue word meaning anything from a superorganism like Gaia, to no more than a catalogue of all living organisms. In the first edition, I tended to use it, as many do, as a synonym for Gaia. At the time, I did not know the full definition of either of them and used them interchangeably for no reason other than literary variation In this edition, the relationship between biosphere and Gaia is like that between your body and you. The biosphere is the three-dimensional geographic region where living organisms exist. Gaia is the superorganism composed of all life tightly coupled with the air, the oceans, and the surface rocks.

It follows that this book is not for hard scientists. If they read it in spite of my warning, they will find it either too radical or not scientifically correct. Yet, I am a scientist and I am deeply committed to science as a way of life. I did not write this book to irritate my colleagues. None of us then knew much about the Earth. I differed from them because the view from space let me see the Earth from th top down, not in the usual reductionist way from the bottom up. The external, holistic, view unexpectedly puts me in tune with both the post–modern world and with mainstream science before i started its love affair with reductionism.

The French Nobel laureate, Jacques Monod, in his book *Chance and Necessity* castigated holistic thinkers like me as ‘very stupid people’. I salute him as most distinguished among scientists but still think that he was wrong and that science needs the top–down approach as much as it needs reduction.

If the whole of present human scientific knowledge were entered in a single book, it would be beyond the ~~comprehension of anyone now alive. Scientists in their whole working lives rarely ever leave~~ a small subsection of a single chapter. While no one could understand the whole book, at least with the top–down holistic look we can see the table of contents. Having said this, I recognize that scientists now, deep into the reduction of a single page are uninterested in the book, or even other chapters of it Broad ideas like Gaia are anathema to them. They see Gaia as metascience, something like a religiou faith and therefore from their deeply held materialistic beliefs, something to be rejected.

Change is in the air, perhaps science grows generous again. Encouraging signs first appeared in Oxford in April 1994, at a scientific meeting to the title 'The Self Regulating Earth'. Here a wish was expressed to see established a forum for the top–down, physiological style discussion of Earth scienc topics. Even opponents of the original Gaia hypothesis, wished for a society where they could discuss ideas outside the essential but limited bottom–up approach of mainstream science. Subsequent meetings in Oxford in 1996 and 1999 expanded and developed a holistic view of the Earth. Now mos scientists appear to accept Gaia theory and apply it to their research, but they still reject the name Gaia and prefer to talk of Earth System Science, or Geophysiology, instead.

This local and partial acceptance of the real science of Gaia, after twenty–six years in the wilderness, was not without conditions. Important among them is the demand that the new science of Gaia, Geophysiology, must be purged of all reference to mystical notions of Gaia the Earth Mother. Even metaphorical phrases such as 'Gaia likes it cool' to express the observation that the Earth syste appears to flourish in glacial times must be cast out. Before Geophysiology is accepted into the ampl but strait–laced bosom of science, it must be scientifically correct.

This means speaking science in its own strict language, heavy and laden with abstract nouns and the passive tense though it may be. The problems of our ailing society inhabiting an unhealthy planet are serious and this is no time to quibble over the rules. Science is almost certainly needed to keep ou civilization alive, and if Gaia is a good model of the Earth, then I must express it in scientific language. It is like the way a soldier has to accept military discipline when enlisting to fight in a just war.

The community of environmentalists include many who claim an ownership of Gaian ideas and they have a case. Jonathan Porritt put it well: Gaia is too important as a focus for Green thought and action to be conscripted by science. Some accused me of betraying Gaia. Fred Pearce, in an entertaining article in the *New Scientist* of May 1994, captured the spirit of that Oxford meeting whe he asked for Gaia to be acknowledged by science and the humanities both.

These are anxious and exciting times and remind me of the days before the Second World War when many free spirits saw the need to accept conscription. They knew that if war was to lead to a ju and successful peace its objectives must be kept in mind as well as the disciplined mechanics of military action. There is no betrayal of Gaia, we need the restraint of scientific conduct for investigation and theory testing and we need the poetry and emotion that moves us and keeps us in good heart while the battle goes on.

As a scientist, I submit wholly to scientific discipline and this is why I sanitized my second book *The Ages of Gaia* and hopefully made it acceptable to scientists. As a man I also live in the gentler world of natural history, where ideas are expressed poetically and so that anyone interested can understand and that is why this book remains almost unchanged. One critic referred to it scathingly a a fairy story about a Greek goddess. In a way, he was right. It was also a long letter to a yet unknown love, with science as such an incidental part as it was in Primo Levi's *Periodic Table*. Written in Ireland perhaps it is Irish in spirit. To my scientist friends who wanted it to lead somewhere else I would say: if you wanted to go there, you should not have started from here.

The old Gaia was an entity that kept herself and all who lived with her comfortable throughout time and season. She worked so that the air, the oceans, and the soil were always fit for life. She was something that almost everyone could understand. I intended Gaia of this first book to enliven and entertain a walk in the countryside or a journey to a new and unvisited place. It tells how the apparen random destructiveness of a forest fire might be part of a way to keep oxygen in the air at the safe level of 21 per cent. It describes how my friend Andrew Watson showed by simple experiments that even 25 per cent of oxygen in the air would be disastrous. Trees could not grow to make forests. With that much oxygen, fire would destroy them while still half grown. No one had thought of the air, or th oxygen, that way before.

In Chapter 6, we take a walk along the seashore, pick up seaweeds and sniff their odd sweet sulphury smell, and wonder about their function in Gaia. I never guessed twenty years ago that these wonderings would lead to what is now a large scientific enterprise employing hundreds of scientists worldwide. What was in truth no more than a nature walk along the shore in Ireland has become a major research. Scientists now seek the connection between the growth of ocean algae and the climat They measure the output of gases that come from the sea because of an algal presence. They observe the oxidation of these gases in the air to make the seeds from which clouds form. They look at the effect of these events on climate and on the way that climate change feeds back on the growth of the algae. It is an investigation in its early stages, full of argument and full of vigour.

Deerfly, although they are as much a part of the natural world as we are, can make a walk through a Canadian forest in summertime a misery. Among the species of scientists, there are similar irritatin types whose careers grow from the blood sucked from large and ill–considered hypotheses. Their existence is needed in the natural selection of theories. Without these gadflies, we would be taking bogus ideas like biospheres in bottles, or cold fusion, seriously. The Gaia hypothesis was a vague speculation before the blood was drawn to leave the leaner and more scientifically acceptable Gaia theory. For this I am grateful to the critics.

During the next and scientifically correct stages in the development of the theory, it may become all but incomprehensible to any but its own scientific practitioners. Do not make the mistake of those disgruntled humanists who will reject Gaia because it is part of a science they do not understand. There is nothing solid in their claim that science is malign or bogus. Science is wonderfully self–cleansing and bad theories have a short life.

Some of the preface of the first edition seems to follow the above text naturally so I have include it as part of what follows. The idea of Mother Earth or, as the Greeks called her, Gaia, has been widel held throughout history and has been the basis of a belief that coexists with the great religions. Evidence about the natural environment accumulates and the science of ecology grows. This has led t speculation that the biosphere may be more than the habitat of all living things. Ancient belief and modern knowledge have fused emotionally in the awe with which astronauts with their own eyes and we by television have seen the Earth revealed in all its shining beauty against the deep darkness of space. Yet, this feeling, however strong, does not prove that Mother Earth lives. Like a religious belief, it is scientifically untestable and therefore incapable in its own context of further rationalization.

The idea of the Earth as a kind of living organism, something able to regulate its climate and composition so as always to be comfortable for the organisms that inhabited it, arose in a most respectable scientific environment. It came to me suddenly one afternoon in 1965 when I was workin at the Jet Propulsion Laboratory (JPL) in California. It came because my work there led me to look a the Earth's atmosphere from the top down, from space. Such a look forces questions about the ~~composition of the air we breathe not previously asked. We all take our first breath of life–sustaining~~ air and from then on take it for granted. We are confident it will be there to breathe as constant in composition as is the Sun constant in its rising and setting. Air is invisible almost intangible but if yo look at it from above, from space you see it as something new, something unexpected. It is the perfe stained glass window of the world, but also it is a strange mixture of unstable, almost combustible gases. The air is a mixture that somehow always keeps constant in composition. My flash of enlightenment that afternoon was the thought that to keep constant something must be regulating it and that somehow the life at the surface was involved.

The quest for Gaia, which began nearly thirty–five years ago has ranged through the territories of many different scientific disciplines, indeed from astronomy to zoology. Such journeys are lively, fo professors jealously guard the boundaries between their sciences. I had to learn a different arcane language in each territory I passed through. In the ordinary way a grand tour of this kind would be extravagantly expensive and unproductive in its yield of new knowledge; but just as trade often still goes on between nations at war, it is also possible for a chemist to travel through such distant disciplines as meteorology or physiology, if he has something to barter. Usually this is a piece of hardware or a technique. I was fortunate to work briefly with A. J. P. Martin, who developed among other things the important chemical analytical technique of gas chromatography. During that time, I added some embellishments that extended the range of his invention. One of these was the so–called electron capture detector. It is a device of exquisite sensitivity, which discovered pesticide residues i all creatures of the Earth, from penguins in Antarctica to the milk of nursing mothers in the USA. It was this discovery that helped Rachel Carson to write her immensely influential book, *Silent Spring*. provided her with the evidence that these toxic chemicals were ubiquitous worldwide. It justified her concern that they threatened the organisms of the biosphere. Electron capture has continued to reveal minute but significant quantities of other toxic chemicals in places they ought not to be. Among thes intruders are: PAN (peroxyacetyl nitrate), a toxic component of smog; the PCBs (polychlorobiphenyls) in the remote natural environment. It has also revealed the presence of the chlorofluorocarbons and nitrous oxide, substances that deplete the strength of ozone in the stratosphere.

Electron capture detectors were undoubtedly the most valued of the trade goods which enabled m to pursue my quest for Gaia through the various scientific disciplines, and indeed to travel literally around the Earth itself. My role as a tradesman made interdisciplinary journeys feasible, but they hav not been easy. The past thirty years have witnessed a great deal of turmoil in the life sciences, particularly in areas where science has been drawn into the process of politics.

When Rachel Carson made us aware of the dangers arising from the mass application of toxic chemicals, she presented her arguments in the manner of an advocate, not a scientist. In other words, she selected the evidence to prove her case. The chemical industry, seeing its livelihood threatened b her action, responded with an equally selective set of arguments, chosen in defence. This may have been a fine way of achieving justice, and perhaps in this instance it was scientifically excusable; but seems to have established a pattern. Since then a great deal of scientific argument and evidence concerning the environment is presented as if in a courtroom or at a public enquiry. I cannot say too often that, although this may be good for the democratic process, it is bad for science. Truth is said to be the first casualty of war. Being used selectively in evidence to prove a case in law also weakens it

The first six chapters of this book are not concerned with matters of social controversy—at least not yet. In the last three chapters, however, which are about Gaia and mankind, I am aware of having moved on to a battleground where powerful forces are in action. President Havel’s moving address, the ~~constant support of Sir Crispin Tickell, Jonathon Porritt, and other leaders gives me reason t~~o fee that Gaia is significant beyond science. If only to warn, that to act for the good of humankind alone i not enough. When I first started this book, twenty–six years ago, the future looked good. There were problems looming with people and the environment but all seemed capable of sensible or scientific solution. Now the prospect is at best doubtful. One of the few certainties about the Earth is that we have changed the atmosphere and the land surface more than it has changed by itself in millions of years. These changes still go on and ever faster as our numbers grow. Ominously nothing yet seems t have happened more noticeable than the ozone hole over Antarctica. Most politicians believe that all we need is growth and trade and that environmental problems can be fixed technologically. This normal human optimism reminds me of a time in London in the Second World War. I had the job of checking the quality of the air in an underground air raid shelter. It was in a disused tube tunnel that ran through the soft mud alongside the River Thames. To my dismay I found that vandals had taken away most of the bolts holding together the steel plates of the tunnel to sell for scrap. It would have taken only a small disturbance to burst the tunnel and flood it. The denizens of the shelter did not seem worried about the possibility of being drowned in mud. They were more frightened by the nois but in my judgement, less dangerous war on the surface above them. In a way we are still taking awa the bolts of the tunnel and feel confident that what we do is harmless because so far nothing has happened.

Shortly after I wrote the first edition, I came across an article by Arthur Redfield in the *America Scientist* of 1958. In it he put forward the hypothesis that the chemical composition of the atmosphe and oceans was biologically controlled. He produced supporting evidence drawn from the distributio of the elements. I am glad that I saw Redfield’s contribution to the development of the Gaia hypothesis in time to acknowledge it. I now know that there were many others who had these and similar thoughts, including the Russian scientist Vernadsky, and G. E. Hutchinson. I most regret my ignorance then of James Hutton, often known as the father of Geology, who in 1785 compared the global cycling of water with the blood circulation of an animal. The notion of Gaia, of a living Earth, has not in the past been acceptable in the mainstream and consequently seeds sown in earlier times d not flourish but instead remained buried in the deep mulch of scientific papers.

In a subject so broadly based as that of this book there was the need for much advice and I thank the many scientific colleagues who patiently and unstintingly gave their time to help me, especially Professor Lynn Margulis who has been my constant colleague and guide. I am also grateful to Professor C. E. Junge of Mainz and to Professor B. Bolin of Stockholm, who first encouraged me to write about Gaia. I thank my colleagues Dr James Lodge of Boulder, Colorado, Sidney Epton of Shel Research Limited, and Professor Peter Fellgett of Reading, who encouraged me to continue the quest

My special thanks go to Evelyn Frazer, who took the draft of this book and most skilfully turned the disordered mosaic of sentences and paragraphs into a readable whole. Finally, I wish to record m debt to my first wife Helen Lovelock, who not merely produced the typescript but also, in her lifetim kept the environment in which writing and thinking were possible. Contrary to all reasonable expectation, life began again for me at 70 with my second wife Sandy Lovelock, for whom it could b said this book was written since her reading it brought us together.

I have listed at the end of the book, arranged by chapter, the principle sources of information and suggestions for additional reading, together with some definitions and explanations of terms and of the system of units of measurement used in the text.

1 *Introductory*

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 als 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 spac biologists Norman Horowitz, whose main objective was to devise ways and means of detecting life o 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 Ver 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. Additiona 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 reve itself to tests based on Earth's life style?' To say nothing of more difficult questions, such as, 'What 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 dissipat 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 reversa of entropy as a sign of life had implanted itself in my mind. It grew and waxed fruitful until, with the help of my colleagues, Dian Hitchcock, Sidney Epton, 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 Laboratorie 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 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 science Data galore had been accumulated on every conceivable aspect of living species, from their outermos 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 grou 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 theoren 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 efficie 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 instan 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 o 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 th 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 itsel 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. suggests, for example, that there is a boundary, or interface, between the ‘factory’ area where the flo 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, o 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 th 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 sola 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 o 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 landfal 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 wel 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 500 million tons of this gas must be introduced into the atmosphere yearly. In addition, there must be some mean 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 constitutin 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 mid–sixties. With some exceptions, notably Rubey, Hutchinson, Bates, and Nicolet, most geochemists regarded the atmosphere as an end–product of planetary outgassing ar 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 hydroge into space, leaving an excess of oxygen behind. Life merely borrowed gases from the atmosphere anc 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 t 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 wit 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 196 three years before the formation of Friends of the Earth and similar pressure–groups brought pollutio problems to the forefront of the public mind.

Like artists, independent scientists need sponsors but this rarely involves a possessive relationshi 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–nationa corporation must be suspect by origin. Others are just as convinced that similar work coming from a 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 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. Muc 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 presenc 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 o magnitude. Disequilibria 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 deriv 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/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 t 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 1968. Perhaps it was poorly presented. It certainly did not appeal to anyone except Lars Gunnar Sillen, the Scandinavian chemist now sadly dead. Lynn Margulis, of Boston University, had the task of editing our various contributions, and four years 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'.

The Gaia of this book is 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 an entertain. The Gaia hypothesis is for those who like to walk or simply stand and stare, to wonder abou 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 travelling, driverless and purposeless, around an inner circle of the sun.

2 *In the beginning*

In scientific usage, an aeon represents 1,000 million years. So far as we can tell from the record of th rocks and from measurements of their radioactivity, the Earth began its existence as a separate body space about 4,500 million years, or four and a half aeons, ago. The earliest traces of life so far identified are to be found in sedimentary rocks formed more than three aeons ago. However, as H. G. Wells put it, the record of the rocks is no more a complete record of life in the past than the books of bank are a record of the existence of everybody in the neighbourhood. Untold millions of early life–forms and their more complex but still soft–bodied descendants may have lived and flourished and passed away without putting anything by for the future, or—to change the simile—without leaving any traces, let alone skeletons for the geological cupboard.

It is not surprising, therefore, that little is known about the origin of life on our planet and still le about the course of its early evolution. But if we review what we know concerning the Earth's beginnings in the context of the universe from which it was formed, we can at least make intelligent guesses about the environment in which life, and potentially Gaia, began, and set about ensuring thei mutual survival.

We know, from observations of events in our own galaxy, that the stellar universe resembles a living population, in which at any time may be found people of all ages from infants to centenarians. As old stars, like old soldiers, fade away, while others expire more spectacularly in an explosive blaz of glory, fresh incandescent globes with their satellite moths are taking shape. When we examine spectro–scopically the interstellar dust and gas clouds from which new suns and planets condense, w find that these contain an abundance of the simple and compound molecules from which the chemica building blocks of life can be assembled. Indeed, the universe appears to be littered with life's chemicals. Nearly every week there is news from the astronomical front of yet another complex organic substance found far away in space. It seems almost as if our galaxy were a giant warehouse containing the spare parts needed for life.

If we can imagine a planet made of nothing but the component parts of watches, we may reasonably assume that in the fullness of time—perhaps 1,000 million years—gravitational forces an the restless motion of the wind would assemble at least one working watch. Life on Earth probably started in a similar manner. The countless number and variety of random encounters between individual molecular components of life may have eventually resulted in a chance association of part which together could perform a life–like task, such as gathering sunlight and using its energy to contrive some further action which would otherwise have been impossible or forbidden by the laws o physics. (The ancient Greek myth of Prometheus stealing fire from heaven and the biblical story of Adam and Eve tasting the forbidden fruit may have far deeper roots in our ancestral history than we realize.) Later, as more of these primitive assembly–forms appeared, some successfully combined an from their union more complex assemblies emerged with new properties and powers, and united in their turn, the product of fruitful associations being always a more potent assembly of working parts, until eventually there came into being a complex entity with the properties of life itself: the first micro–organism and one capable of using sunlight and the molecules of the environment to produce its own duplicate.

The odds against such a sequence of encounters leading to the first living entity are enormous. On the ~~other hand, the number of random encounters between the component molecules of the Earth~~'s primeval substance must have been incalculable. Life was thus an almost utterly improbable event with almost infinite opportunities of happening. So it did. Let us at least assume that it happened in this way rather than by the mysterious planting of a seed, or the drift of spores from elsewhere or indeed by outside intervention of any kind. We are not primarily concerned with the origin of life bu with the relationship between the evolving biosphere and the early planetary environment of the Eart

What was the state of the Earth just before life began, perhaps three and a half aeons ago? Why was our planet able to bear and sustain life when its nearest siblings, Mars and Venus, apparently failed? What hazards and near disasters would have faced the infant biosphere and how might Gaia's presence have helped to surmount them? To suggest possible answers to these intriguing questions, v must first return to the circumstances in which the Earth itself was formed, some four and a half aeon ago.

It seems almost certain that close in time and space to the origin of our solar system, there was a supernova event. A supernova is the explosion of a large star. Astronomers speculate that this fate may overtake a star in the following manner: as a star burns, mostly by fusion of its hydrogen and, later, helium atoms, the ashes of its fire in the form of other heavier elements such as silicon and iron accumulate at the centre. If this core of dead elements, no longer generating heat and pressure, shoul much exceed the mass of our own sun, the inexorable force of its own weight will be enough to cause its collapse in a matter of seconds to a body no larger than a few thousand cubic miles in volume, although still as heavy as a star. The birth of this extraordinary object, a neutron star, is a catastrophe of cosmic dimensions. Although the details of this and other similar catastrophic processes are still obscure, it is obvious that we have here, in the death throes of a large star, all the ingredients for a va nuclear explosion. The stupendous amount of light, heat, and hard radiation produced by a supernova event equals at its peak the total output of all the other stars in the galaxy.

Explosions are seldom one hundred per cent efficient. When a star ends as a supernova, the nucle explosive material, which includes uranium and plutonium together with large amounts of iron and other burnt–out elements, is distributed around and scattered in space just as is the dust cloud from a hydrogen bomb test. Perhaps the strangest fact of all about our planet is that it consists largely of lumps of fall–out from a star–sized hydrogen bomb. Even today, aeons later, there is still enough of the unstable explosive material remaining in the Earth's crust to enable the reconstitution on a minut scale of the original event.

Binary, or double, star systems are quite common in our galaxy, and it may be that at one time ou sun, that quiet and well–behaved body, had a large companion which rapidly consumed its store of hydrogen and ended as a supernova. Or it may be that the debris of a nearby supernova explosion mingled with the swirl of interstellar dust and gases from which the sun and its planets were condensing. In either case, our solar system must have been formed in close conjunction with a supernova event. There is no other credible explanation of the great quantity of exploding atoms still present on the Earth. The most primitive and old–fashioned Geiger counter will indicate that we stan on fall–out from a vast nuclear explosion. Within our bodies, no less than 500,000 atoms rendered unstable in that event still erupt every minute, releasing a tiny fraction of the energy stored from that fierce fire of long ago.

The Earth's present stock of uranium contains only 0.72 per cent of the dangerous isotope U235. From this figure it is easy to calculate that about four aeons ago the uranium in the Earth's crust would have been nearly 15 per cent U235. Believe it or not, nuclear reactors have existed since long before man, and a fossil natural nuclear reactor was recently discovered in Gabon, in Africa. It was in action ~~two aeons ago when U235 was only a few per cent. We can therefore be fairly certain that~~ the geochemical concentration of uranium four aeons ago could have led to spectacular displays of natur nuclear reactions. In the current fashionable denigration of technology, it is easy to forget that nuclea fission is a natural process. If something as intricate as life can assemble by accident, we need not marvel at the fission reactor, a relatively simple contraption, doing likewise.

Thus life probably began under conditions of radioactivity far more intense than those which trouble the minds of certain present–day environmentalists. Moreover, there was neither free oxygen nor ozone in the air, so that the surface of the Earth would have been exposed to the fierce unfiltered ultra–violet radiation of the sun. The hazards of nuclear and of ultra–violet radiation are much in min these days and some fear that they may destroy all life on Earth. Yet the very womb of life was flooded by the light of these fierce energies.

There is no paradox here. The present dangers are real but tend to be exaggerated. These rays are part of the natural environment and always have been. When life was first developing, the destructive bond–severing power of nuclear radiation may even have been beneficial, since it must have hastened the essential process of trial and error by dismantling the mistakes and regenerating the basic chemical spare parts. Above all, it would have hastened the production of random new combinations until the optimum form emerged.

As Urey has taught us, the Earth's primeval atmosphere would have been blown away during the early stages when the sun was settling down. Our planet may have been for a while as bare as the moon is now. Later, the pressure of the Earth's own mass and the pent–up energy of its highly radioactive contents heated up the interior until gases and water vapour escaped to form the air and th oceans. We do not know how long it took to produce this secondary atmosphere, nor do we have evidence of its original composition, but we surmise that at the time when life began the gases from the interior were richer in hydrogen than those which now vent from volcanoes. The organic compounds, component parts of life, require that some hydrogen is available in the environment both for their formation and for their survival.

When we consider the elements from which the compounds of life are made, we usually think firs of carbon, nitrogen, oxygen, and phosphorus, and then of a miscellany of trace elements, including iron, zinc, and calcium. Hydrogen, that ubiquitous material from which most of the universe is made and which occurs in all living matter, is more often taken for granted. Yet its importance and versatility are paramount. It is an essential part of any compound formed by the other key elements o life. As the fuel which powers the sun, it is the primary source of that generous flux of free solar energy which enables life's processes to start and keep going. Water, another life–essential material which is so common that we tend to forget it, is two–thirds hydrogen in atomic proportion. The abundance of free hydrogen on a planet sets the reduction–oxidation, or redox, potential, which is a measure of the tendency of an environment to oxidize or reduce. (In an oxidizing environment an element takes up oxygen, thus iron rusts. In a reducing, hydrogen–rich, environment an oxide compound tends to shed its oxygen load, thus rust turns back to iron.) The abundance of positively charged hydrogen atoms also sets the balance between acid and alkaline, or as a chemist would call it the pH. The redox potential and the level of pH are two key environmental factors which determine whether a planet is fair or foul for life.

The American Viking spacecraft which landed on Mars and the Russian spaceship Venera which landed on Venus have both reported that no life can be seen. Venus has by now lost almost all her hydrogen and is in consequence hopelessly barren. Mars still has water and therefore chemically

bound hydrogen, but its surface is so oxidized as to be bereft of the organic molecules from which lif
might be built. Both planets are not only dead but now never could bear life.

Although we have very little direct evidence about the chemistry of the Earth when life began, we do know that the atmosphere was not oxidizing like now and that the organic chemicals of life could have formed and persisted long enough for life to start. It seems probable that aeons ago Mars, Venus and the Earth had similar surface compositions, rich in carbon dioxide and water and with traces of th reducing gases hydrogen, methane, and ammonia also present; but just as iron rusts and rubber perishes, time, that great oxidizer, ensures that even a planet will wither and become barren as that life–essential element hydrogen escapes to space.

The Earth must therefore have had a slightly reducing atmosphere and strongly reducing oceans a the time when life began. The flux of reducing materials from the Earth’s interior, like the ferrous form of iron and sulphur, were vast and kept free oxygen from appearing in the air for more than an aeon. An important gas for life of the early atmosphere was carbon dioxide. Scientists now think that its presence as the dominant atmospheric gas acted as a blanket that kept our planet warm at a time when the sun was less radiant than it is now.

The history of the Earth’s climate is one of the more compelling arguments in favour of Gaia’s existence. We know from the record of the sedimentary rocks that for the past three and a half aeons the climate has never been, even for a short period, wholly unfavourable for life. Because of the unbroken record of life, we also know that the oceans can never have either frozen or boiled. Indeed, subtle evidence from the ratio of the different forms of oxygen atoms laid down in the rocks over the course of time strongly suggests that the climate has always been much as it is now, except during glacial periods or near the beginning of life when it was somewhat warmer. The glacial cold spells—Ice Ages, as they are called, often with exaggeration—affected only those parts of the Earth outside latitudes 45° North and 45° South. We are inclined to overlook the fact that 70 per cent of the Earth’s surface lies between these latitudes. The so–called Ice Ages only affected the plant and animal life which had colonized the remaining 30 per cent, which is often partially frozen even between glacial periods, as it is now.

We may at first think that there is nothing particularly odd about this picture of a stable climate over the past three and a half aeons. The Earth had no doubt long since settled down in orbit around that great and constant radiator, the sun, so why should we expect anything different? Yet it is odd, and for this reason: our sun, being a typical star, has evolved according to a standard and well established pattern. A consequence of this is that during the three and a half aeons of life’s existence on the Earth, the sun’s output of energy will have increased by twenty–five per cent. Twenty–five per cent less heat from the sun would imply a mean temperature for the Earth well below the freezing point of water. If the Earth’s climate were determined solely by the output from the sun, our planet would have been in a frozen state during the first one and a half aeons of life’s existence. We know from the record of the rocks and from the persistence of life itself that no such adverse conditions existed.

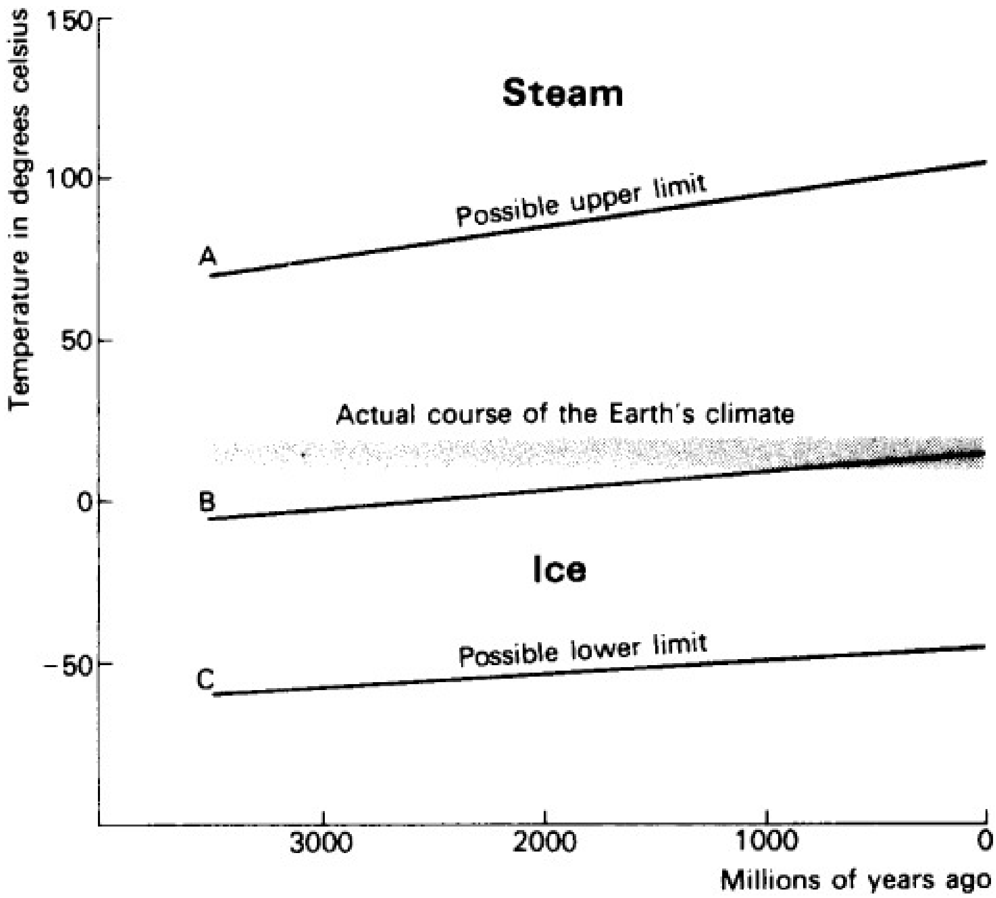
If the Earth were simply a solid inanimate object, its surface temperature would follow the variations in solar output. No amount of insulating clothing will indefinitely protect a stone statue from winter cold or summer heat. Yet somehow, through three and half aeons, the surface temperatur has remained constant and favourable for life, much as our body temperatures remain constant whether it is summer or winter and whether we find ourselves in a polar or tropical environment. It might be thought that the fierce radioactivity of early days would be enough to keep the planet warm In fact simple calculations based on the very predictable nature of radioactive decay indicate that although these energies keep the interior incandescent, they have little effect on surface temperatures

Planetary scientists have offered several explanations of our constant climate. Carl Sagan and his collaborator Dr Mullen, for example, have recently suggested that in earlier times, when the sun was dimmer, the presence of gases such as ammonia in the air helped to conserve such heat as the Earth received. Certain gases, like carbon dioxide and ammonia, absorb infra–red heat radiation from the Earth’s surface and delay its escape to outer space. We now think that ammonia could not have been present at a sufficient concentration; it is much more likely that carbon dioxide served as the gaseous greenhouse that kept the planet warm.

They are the gaseous equivalent of warm clothing. They have the additional advantage over clothing of being transparent to the incoming visible and near infra–red radiation of the sun which conveys to the Earth nearly all of the heat it receives.

Other scientists, especially Professor Meadows and Ann Henderson–Sellers of Leicester University, have suggested that in earlier times the Earth’s surface was darker in colour and therefore absorbed more of the sun’s heat than it does now. The proportion of sunlight reflected to space is called the albedo, or whiteness, of a planet. If its surface is completely white, it will reflect all sunlight to space and will be very cold. If it is completely black, all sunlight will be absorbed and it will be warm. A change in the albedo could obviously compensate for the lesser heat of a dimmer sun. At the present time the Earth’s surface is appropriately of an intermediate colour and half covered with clouds. It reflects about 45 per cent of the incoming sunlight.

It was warm and comfortable for embryo life, in spite of the weaker flux of heat from the sun. The only explanations offered to account for this ‘unseasonal winter warmth’ are protection by the ‘greenhouse’ gas carbon dioxide, or a lower albedo due to a different distribution of the Earth’s land masses at that time. Both are possible explanations up to a point. It is where they break down that we catch our first glimpse of Gaia, or at least of the need to postulate her existence.



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