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Thermodynamics and the recognition of alien biospheres

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The presence of a mature biosphere is likely to change surface and atmospheric composition and the energy balance of a planet away from that of the abiotic state. Is it possible that such a change might be detected from afar by astronomical techniques and so form the basis of a test for the presence of a planetary biosphere? A distant view of the Earth in this context shows that certain of its thermodynamic properties are recognizably different from those of the other terrestrial planets, which presumably are lifeless. The general application of this test for the remote detection of other biospheres will be discussed, as will some implications of this way of viewing biospheres on the nature and organizations of life on Earth.

INTRODUCTION

It is a cliché of science fiction for the captain of a space craft when approaching a new planetary system to call his exobiological officer and ask 'do any of those planets bear life?'. The operation by this officer of a remote sensing device soon provides a confident answer, yes or no. One purpose of this paper is to consider the possible basis of such a device.

To operate at planetary orbital distances the device would need to observe and to measure physical rather than biological properties. Guidance for the choice of the specific properties to measure comes from a consideration of the process of life and the act of recognition within a context which includes also instrument design. A branch of science large enough to encompass these three different subjects is thermodynamics. From the early technology of the steam engine to the intricacies of the present technosphere, engineers have used thermodynamics as a source of inspiration and of recipes; so it may be for instruments and procedures for the detection of life.

There are several reasons for choosing to seek a biosphere rather than any of its component parts; with a telescope it is easier to see an elephant than a virus and where a planetary system is viewed from afar it seems prudent to go for the largest unit of all, namely, the biosphere itself. A physical, in contrast to a biological, approach to planetary life detection was suggested (Lovelock 1965) and later Hitchcock & Lovelock (1967) proposed that the knowledge of the chemical composition of a planetary atmosphere itself constituted a life detection experiment. It was further suggested that sufficient information for these purposes might be gathered by astronomical measurements in the infrared.

At that time it was generally believed that the abundance of the atmospheric gases was determined by equilibrium chemistry. Strangely this belief more or less peacefully coexisted with the certain fact that these gases were cycled by the biosphere with geometric mean residence times measured in thousands of years. Plausibility was kept alive by the hypothesis that the biology had adapted to the chemical environment and merely borrowed and returned gases without changing their abundance in the atmosphere. In such a climate of opinion the notion of life detection through atmospheric analysis was not well received. In the years since 1965 interest in the natural environment has intensified and it is now recognized that the atmospheres, oceans and surface rocks are subject to active rather than passive biological cycling. Recently Lovelock & Margulis (1974) have offered an alternative explanation of the current atmospheric abundance. In this, the Gaia hypothesis, the biosphere is seen as a cybernetic control system able to adapt the Earth environment to an optimum for its needs. In the hypothesis this optimization applies not only to atmospheric abundance but also to the climate, the surface pH, and other important planetary properties. Much of what follows is a reconsideration of the physical basis of life detection from this new view point.

Physical basis

The instrument required is an astronomical telescope and spectrometer whose purpose is to gather information on the physical and chemical state of the planet in view. The problem lies not in the design of the instrument but in the search procedure and in the interpretation of the information it gathers. We are so evolved to recognize terrestrial life by primary instinctive processes, that the basis of this recognition is rarely analysed or questioned. To recognize alien life at a distance through a telescope we may need something more than our internal terrestrial life recognition programme. Thermodynamics provides clues and a guidance for our search for life in three principal ways as follows:

First, discussions on the physical nature of life (Schrodinger 1944; Bernal 1951) reach agreement at the conclusion which briefly may be stated: in accord with the second law of thermodynamics, life can be considered as 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 of free energy taken in from the environment and subsequently rejected in a degraded form. For the purpose of this discussion the difficult phrase 'decrease their entropy' could be replaced by the more comprehensible one 'increase their information'.

The special contribution to our problem of this early approach to the definition of life as a process, is that it establishes a boundary between that in which entropy is reduced, and the outside world to which it is excreted. Thus if the life of a planet is chemically based and driven by solar energy, gaseous products may diffuse into the atmosphere and by their presence cause a departure from the equilibrium state. In these circumstances the boundary of the system in which entropy is reduced is the interface between the atmosphere and space. It follows that the flux of entropy into space must be increased by the presence of life and may be recognizable in terms of unexpected features in the planetary radiation balance. More important though is the implication that the atmosphere in such circumstances is a part of the system within which entropy is reduced and not just an external environment for life.

Secondly, it is intuitive to link life as a system with those processes which occur when the gradient of free energy is larger than a certain value. Such a limit is well recognized in fluid dynamics as the Reynolds number which marks the onset of vorticity. Like life, vortices establish characteristic recognizable forms with life-spans and histories, and when they form confer a new sort of dynamic stability upon their environment. On the larger scale in the atmosphere itself such vorticity occasionally evolves to the intricate structure of a hurricane with its interdependent cooperative system of vortices and a recognizability great enough to qualify for personal naming. A recent development of the thermodynamics of irreversible processes (Prigogine 1973), goes some way towards the legitimization of these intuitions. Just as the thermodynamics of the steady state (reviewed by Denbigh 1951) grew from the classical equilibrium thermodynamics, so, from the thermodynamics of the steady state is developing what might be called 'the thermodynamics of the unsteady state'. It is essentially concerned with the region where the gradient of free energy is sufficient for any perturbation to initiate an instability. The importance of this development for the problem of life detection is that it provides a formal distinction between the irreversible processes of the inorganic state, such as the conduction of heat, and those of the 'unsteady state' in which life is included. Thus the initiation of life requires not only the assembly of components but also the condition of the unsteady state where the free energy flux is of sufficient magnitude.

The uncharted seas of fluid dynamics have been navigated without the aid of fundamental constants by the introduction of a set of dimensionless numbers. It might be similarly useful in the analysis of life systems to have analogues of the Peclet, Weber and Reynolds numbers. These could be used to categorize the conditions of a planet so that those within the appropriate ranges of the numbers might be expected to bear life whereas those outside the range would not. Maelstroms do not develop in duck ponds neither could life start or continue in an environment which was otherwise ideal, but which lacked a free energy gradient of sufficient quantum potential. Such may well be the conditions deep on Jupiter, warm, damp, with all of the chemical components but lacking free energy. The possibility that convection may convey sufficient reactive molecular species from the upper atmosphere leaves open the question of the possibility of life on Jupiter.

The third contribution from thermodynamics to the problem of recognizing life comes from Boltzman's expressions for entropy (S) in terms of the probability (P) of a molecular distribution:

$$S = k \ln P. \tag{1}$$

The classical definition of entropy is physically precise but conceptually obscure. Boltzman's definition by contrast gives a direct physical insight into the nature of entropy. The very low entropy of living systems suggests a molecular configuration of extreme improbability when viewed against the highly probable equilibrium background.

Although its origins were independent, the phenomenological information theory follows naturally from Boltzman's fundamental expression. This theory was yet another part of thermodynamics developed by and for engineers (Shannon & Weaver 1963). It carries the function of state, entropy, to that practical level which we may need for our 'telebioscope'.

Information (I) in a thermodynamic sense can be defined as the difference between the entropy (S_0) of a system whose components are at equilibrium and the entropy of the system (S) when assembled so that:

$$I = S_0 - S \tag{2}$$

but $(S_0 - S)$ can be expressed in classical thermodynamic terms so that:

$$I = (E + P_0 V - T_0 S - \Sigma \mu i_0 Ni)/T_0. \tag{3}$$

The quantities E, P, V, T are respectively; internal pressure, pressure, volume and temperature. $\Sigma \mu i_0 Ni$ expresses the chemical potential and abundance of the various molecular species present. Quantities qualified by the subscript 0 are those of the equilibrium state. This expression developed by Evans (1969) is described in an eloquent account of the relation between information and energy by Tribus & McIrvine (1971). The quantities on the right hand side of equation (2) are all either directly observable or can be deduced from the information gathered of a planet by a telescope.

Can we use this approach to distinguish planets which bear life from those which merely bear the short lived dissipative structures of proto life?

These are the guide lines drawn from physical theory. Now let us see if the evidence which could reasonably be gathered of a distant planet can be used to measure the probability of the presence of life.

Experiment design

Let us assume that the planet can be seen clearly enough through the telescope to provide the following information:

(1) Surface temperatures to within ± 20 K.

(2) The presence of bulk water and ice and its surface distribution.

(3) The atmospheric abundance of chemically active gases down to parts per 10^8 by volume.

(4) The distribution of temperature pressure and chemical composition with altitude and with surface coordinates.

The resolution of this last measurement should be sufficient to distinguish between at least the major mixing zones of the planet. For the Earth this would include the north and south hemispheres, the troposphere, the stratosphere and the upper atmospheric regions.

The methods are already to hand to gather most of these quantities for a planet such as Mars from an Earth-orbiting space craft. The instrumental methods would be spectroscopic and range from the short ultraviolet to the far infrared. Such powerful information gathering methods as multiplex spectrometry (Fellgett 1969) would be used. Connes & Connes (1966) and Kaplan (1967) have already shown, using infrared multiplex spectrometry, that it is possible even from the Earth's surface to detect trace components such as HCl and HF in the Venus atmosphere. To gather the information requires no visionary instrumental development, merely some improvements in current hardware.

This approach to life detection assumes that the life is chemically based, that it is sited at the planetary surface and that it uses the atmosphere as a transport medium and storage space for raw materials. Even if it is possible to distinguish significantly the departure from equilibrium associated with life, it can only apply if the life in question has modified that part of the planet which is observable. It might be that life was too sparse or existed below the planetary surface, in either case neither it nor its effects might be visible. There are reasons for believing, however, that once life is initiated on a planet it can only persist if it is able to control the planetary environment. This ability may be an important evolutionary step in the early stages of life. The early growth of life on a planet will certainly change the surface and atmospheric composition and such changes could easily alter the radiation environment of the planet both with respect to thermal and to ultraviolet radiation, to a state unfavourable to life. A failure to learn to control the planetary conditions at this early stage could be fatal. Life as a going concern is likely to be intense and to have profoundly modified the planetary physical and chemical environment.

The atmospheres of planets like the Earth with abundant surface water are not very stable in a physical sense. Rasool & DeBergh (1970) comment that had the Earth originated 9.5×10^6 km nearer to the Sun it would have an atmosphere more like that of Venus with high surface temperatures and a runaway greenhouse state. Similarly others (Manabe 1971; Budyko 1966) have commented that a comparatively small fall in temperature, consequent upon a slight decrease in solar output, would have produced freezing conditions throughout the planet. Neither of these states is likely to favour the existence of life, but almost all biologists would agree that abundant water is essential for the development and continuation of life.

Figure 1 illustrates the problem of the Earth's surface temperature. The fact of the persistence of life and the evidence of the geological record all show that for 3×10^9 years, at least, surface temperatures have not changed appreciably and are within the shaded zone of the figure. Some, possibly unwise, astronomers have used this as evidence that the Sun's output has not changed over the same period. Yet the consensus of astronomical opinion is that stellar evolution requires the output of a star to increase exponentially with time. For the Sun 40 % increase is the mean of a range of estimates (Sagan & Mullen 1972). Figure 1 also shows the expected surface temperature, as curve A, if the present atmospheric composition has persisted back through time and the solar output of energy had increased 40 % in 4×10^9 years. This curve is unrealistic, however, for even a few per cent fall in solar output would have triggered an ice age. Budyko (1969) has calculated that a slight further reduction in solar output would lead to widespread snow and ice cover, stabilized by an albedo increase to about 0.8, as the entire surface froze and with surface temperatures according to curve C. In a similar manner any slight increases in solar output or decreases in loss of heat from the Earth would through positive feedback lead to overheating and runaway greenhouse

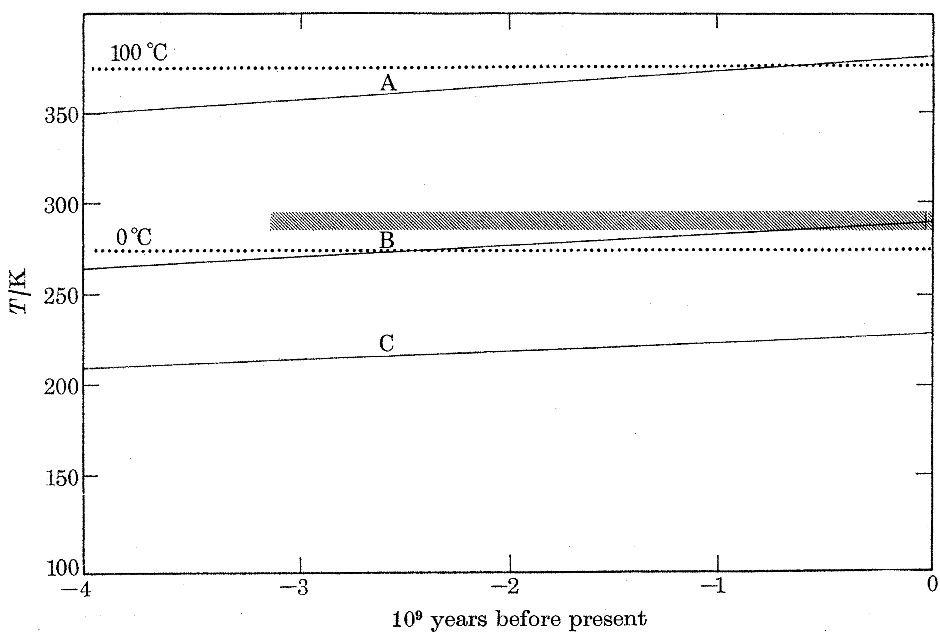

FIGURE 1. The evolution of the Earth's surface temperature assuming that the output from the Sun increased by 40 % during a period of 4×10^9 years. Curve B assuming atmospheric composition was constant at its present values. Curve A, runaway greenhouse conditions assuming an atmosphere in which water vapour was the principal component. Curve C, conditions of widespread ice and snow cover with surface albedo of 0.8. The shaded region indicates the probable course of the Earth's surface temperature during the past 3×10^9 years.

conditions as indicated by curve A. Sagan & Mullen (1972) have suggested that the conditions of curve C were avoided in the past by the biological production of ammonia which served as a greenhouse gas in the atmosphere. Their suggestion is supported by the evidence of table 3 which shows that even today the ammonia flux from the biosphere is substantial and before oxygen was prevalent would probably have been sufficient to sustain an effective greenhouse. The blind production of ammonia by the biosphere is however unlikely to have been enough. Such is the instability of the optimum climate that some means of sensing the temperature and the ammonia concentration and some means of controlling the production appears also to be necessary.

Lovelock & Margulis (1974) and Margulis & Lovelock (1974) have developed the Gaia hypothesis that the biosphere has colligative properties which enable it to control at least the following planetary variables:

(1) Surface temperatures.
(2) Atmospheric composition.
(3) Surface and ocean pH.
(4) Ocean composition.
(5) Materials balance.

In this hypothesis the biosphere is, like its constituent plant and animal parts, seen as a complex cybernetic system with the capacity to keep its internal environment in homeostasis to its advantage. At present Gaia is seen only in hypothesis, but if we can establish the reality of planetary homeostasis for the Earth then it may also be a general characteristic of biospheres. If it is their recognition from afar will be much easier.

Experimental evidence

Now let us consider the information available about the planets Jupiter, Mars, Earth and Venus in this context. To keep within the constraints of a realistic experiment the information about the Earth is restricted to that which could be gathered from an observatory on a Mars orbiting spacecraft.

Figure 2 shows as a set of histograms the chemically reactive gases of the four planets; also included are the gases of a hypothetical abiological Earth. The gas concentrations are expressed in logarithmic units so that the minor constituents can be compared as well as the principal gases. Table 1 lists the pH, pE and the chemical free energy of the planetary atmospheres. The values are calculated from the data of figure 2. Table 2 lists some chemical and thermodynamic information concerning the gases of the present terrestrial atmosphere. The table includes estimates of the departure of the expected chemical equilibrium concentration; these were taken from the calculations of Sillen (1966) and of Dayhoff, Lippencott, Eck & Nagarajan (1967). The calculations of Dayhoff *et al.* (1967) did not take into account the oceans and the crust of the Earth. Table 2 does.

The outstanding difference between the Earth and the other planets is the simultaneous presence of the reducing gases H_2, CH_4 and NH_3 and of oxygen. If the gases of the atmosphere were allowed to react among themselves and with the crustal rocks and ocean the final equilibrium to be expected is that shown in figure 2 for a sterile Earth. It has been repeatedly stated by chemists (see especially Hutchinson 1954) that molecular nitrogen is not the expected compound of the element. Equilibrium calculations strongly favour the NO_3^- ion in the sea. The reversion of the present atmosphere to equilibrium would release 76 kJ/mol, of O_2 almost entirely from the oxidation of nitrogen. No such free

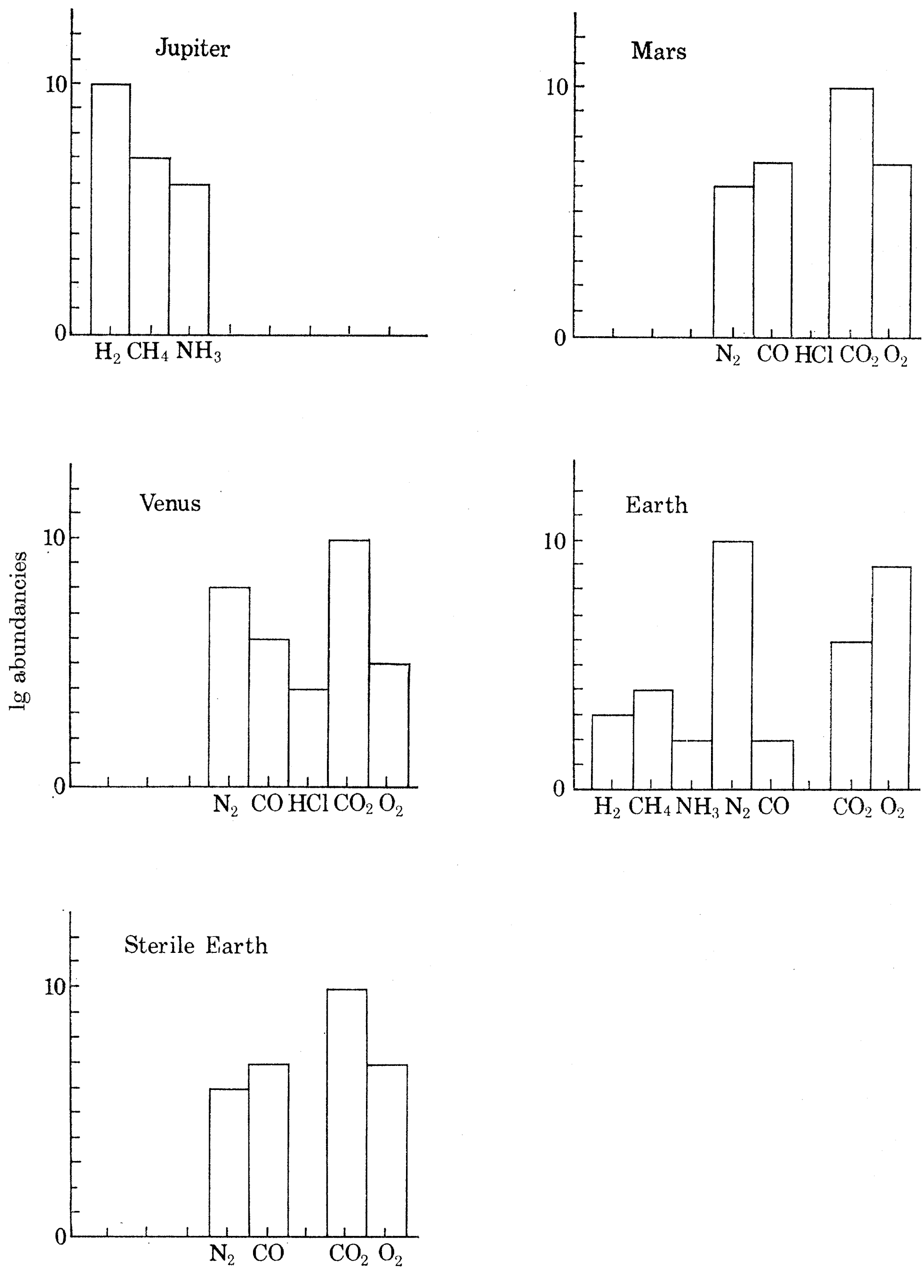

FIGURE 2. The abundance of gases in the planetary atmospheres. Vertical scale logarithm to the base 10 of the abundances.

energy of 'combustion' is available for the other planetary atmospheres and this is one of the several items of evidence which distinguishes the Earth from the other planets.

The free energy released by the combustion of the trace gases CH_4, etc., is trivial compared with that from nitrogen. How then do we interpret the evidence of their presence in an oxidizing atmosphere as indicative of life? One index is the extent of departure from equilibrium expectations; all of the gases listed are more than 10 orders of magnitude, some nearly 30 orders, more abundant than expected. Perhaps the fact that these astonishing disequilibria concerned only

TABLE 1

planet	pH	pE	F†/J mol^{-1}
Jupiter	11	−7	<1
Mars	?	6	13
Earth	8	12.5	5.5×10^4
Venus	1	6	5

† F is the chemical potential energy of the atmosphere.

TABLE 2

gas	abundance (mol fraction)	flux 10^{13} mol/year	disequilibrium†	oxygen consumption 10^{13} mol/year	energy‡ (%)
N_2	0.8	3.6	10	10.8	3.6
CH_4	1.5×10^{-6}	6	30	12	4
H_2	5×10^{-7}	4.4	30	2.2	0.7
N_2O	3×10^{-7}	1.4	13	3.5	1.2
NH_3	1×10^{-8}	8.8	30	3.9	1.3

† Disequilibrium, ratio of found to expected abundance in $\log_{10}$ units.
‡ Energy % of the photosynthetic energy of the biosphere used to cycle the gas listed.

trace gases, led earlier investigators to conclude that the simultaneous presence of for example CH_4 and oxygen was not good evidence for the presence of life. With the notable exception of Radmer & Kok (1971) exobiologists preferred the discovery of some more life characteristic compound such as a terpene as evidence. A simple molecule such as CH_4 could have come from geochemical sources, it was only equivocal evidence for life.

When considered singly and in isolation, plausible inorganic origins can be assigned to most of the atmospheric trace gases listed in table 2, but when the ensemble is considered together with oxygen we have something so unusual as to be beyond any credible inorganic chemistry. Any lingering doubts are dispelled by a consideration of the fluxes of these gases. To sustain the present concentration of methane requires a flux of 10^{15} g/year and also equally significantly, a flux of 4×10^{15} g of oxygen, since this much is removed in the oxidation of methane. Such a flux of methane would require that all of the crustal carbon was turned over every 10^8 years. This is normal for a biosphere but incredible as an accident of inorganic chemistry; especially since all reintroductions of CH_4 to the atmosphere would require its resynthesis from CO_2 in an oxidizing environment. In addition the only abiological source of oxygen is water photolysis in the upper atmosphere; that available from this source is 4×10^{11} g/year, far too small to account for the losses due to methane oxidation. By taking the two gases together the need for some mechanism which can explain their bulk synthesis at the surface is revealed. This could only be a biosphere. The same arguments can be used with equivalent force about other trace gases H_2 and N_2O. Table 2 also lists their fluxes and the energy required to sustain their concentration in the atmosphere. The flux values used in these arguments do not have to be directly measured but can be deduced from the known chemistry of these compounds in the presence of sunlight.

If it still seems more convincing evidence of life on Earth to find terpenes or other 'life characteristic molecules' at near the limit of detection it should be recalled that the history of science is filled with disappointments suffered when such single items of evidence are used; misinterpretation, contamination or even fraud are often the alternative explanation. Moreover, the discovery of almost any biochemical in a neutral or reducing environment, even a protein, would not be conclusive evidence of life. The discovery of even a simple reduced carbon compound such as methane in sufficient quantity in an oxidizing atmosphere is, however, strong evidence for a dynamic system which is making it.

Other biospheres

Even though the discovery of life on Earth through the recognition of its biosphere may not be difficult it does not follow that this is a generality. We cannot yet test the method against other planetary biospheres, but we can ask could it have detected past biospheres of the Earth. We know that life has existed on this planet for 3×10^9 years and although the view is poor from this distance in time some of the larger features can be seen. When life began conditions were reducing, perhaps not as much as on Jupiter but certainly more reducing than Mars is now. Figure 3 is taken from the calculations of Sillen (1966) and shows the variation in the expected equilibrium concentrations of different atmospheric gases with pE. pE is defined as $-\lg \bar{e}$ and is a convenient measure of redox potential. The diagram illustrates the presence of three fairly well defined chemical zones. Below a pE of -5 are the extreme reducing conditions; these are typical of the large outer planets with an abundance of free hydrogen in the atmosphere and also the reduced gases NH_3 and CH_4 as normal equilibrium components. Between a pE of -5 and $+5$ there is a neutral region where gaseous nitrogen is the expected compound of that element and finally at pE values above $+5$, where oxygen makes its first appearance as the free gas, are the conditions of the present terrestrial planets. At these high pE values nitrogen is stable as the nitrate ion, provided that there are oceans and/or a sufficiently high surface pH.

The Earth's biosphere has lived through all of these redox ranges during its evolution so that if other biospheres have a similar basis they may be found in any one of them. Life tolerates large ranges of redox potential; indeed an important segment of the present biosphere are the anaerobic muds, in which conditions closely similar to those of the outer planets are still maintained. Conversely it seems probable that when conditions were reducing on Earth there were important segments of the biosphere which maintained local highly oxidized regions. It

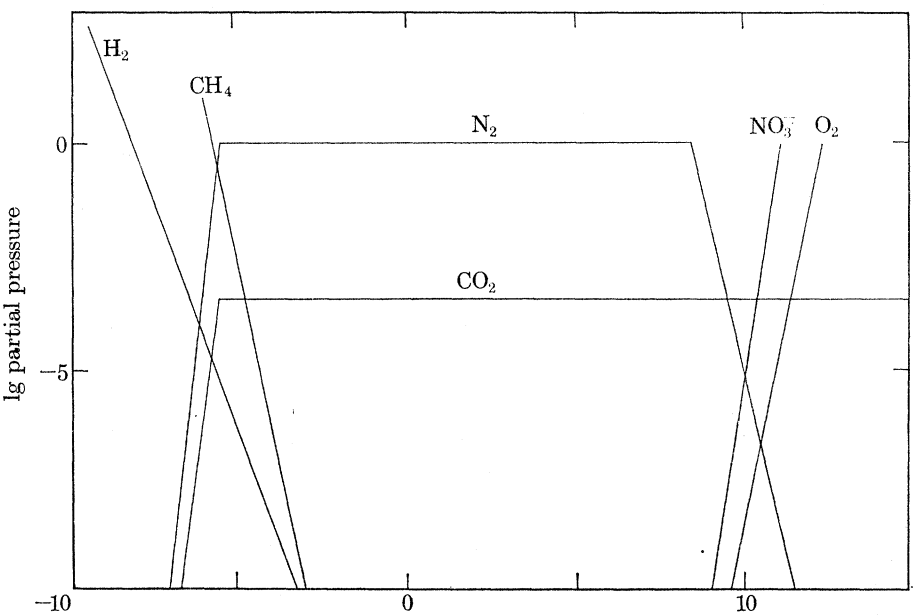

FIGURE 3. Chemical equilibria among atmospheric gases at redox potentials from pE −10 to pE +15. Vertical axis is the logarithm to base 10 of the partial pressure.

follows that the current redox potential of a planet merely establishes the background against which the chemical disequilibrium of life is revealed. If we assume as the general properties of a biosphere: that soon after the start of life a biosphere with cybernetic capacity is established; that the planet is developed to the limit of its resources and of the solar energy it receives; that it is maintained at optimum conditions for whatever is the current biosphere; then table 3 indicates some of the changes which might reveal its presence from a distant view. Under reducing conditions the anomalies to be expected of a biosphere will be the presence of oxidizing gases such as oxygen or nitrous oxide. In terms of their free energy potential other gases such as ethylene or acetylene, with their large stores of molecular energy, constitute a type of oxidant in a reducing atmosphere and their presence in sufficient quantity or at a sufficient disequilibrium might also be indicative of life. Anomalously low concentrations of gases such as NH_3 and CH_4 would add their weight to the total picture of recognizability. Other clues such as gases which might change the planetary radiation balance are listed in table 3.

For a planet with a neutral atmosphere the same considerations apply except that here the anomalies might be between pairs or sets of gases at low concentrations, rather than between a gas and its background oxidizing or reducing environment. Thus the simultaneous presence at low levels of, for example, nitrous oxide and methane would be suggestive of an unusual disequilibrium. The 'greenhouse gases' which might be present in the neutral environment would be NH_3, H_2S and perhaps also dimethyl sulphide. For the oxidizing environment we return to our familiar contemporary conditions which have already been discussed.

TABLE 3

	reducing pE < −5	neutral pE −5 to +5	oxidizing pE > 5
background gases	H_2 CH_4	N_2 CO_2 CO	O_2 CO_2
possible biological indicators	O_2 H_2O $CH{\equiv}CH$, $CH_2{=}CH_2$	O_2 and CH_4 N_2O and NH_3 H_2	CH_4 NH_3 H_2 N_2O
greenhouse gases	NH_3, H_2S, CH_3SCH_3, etc. H_2O	NH_3 CO_2 CH_3SCH_3 H_2O	CO_2 H_2O

Table 3 should not be regarded as a prescription for the discovery of alien biospheres. The proper approach is to gather all of the evidence available and to extract from it the information about the entropy anomaly of the planet under observation.

What of truly alien biospheres? The universe appears to be littered with the spare parts from which our current chemical life form is composed. From this fact and from our knowledge of properties of the elements it seems unlikely that other, for example, silicon based life forms are likely to have evolved. On the other hand we have ample experience of the possibility of life based on electronic and mechanical contrivances; a biosphere of this form would evolve presumably from a chemical one perhaps starting in symbiosis with it. Could we recognize such a biosphere? If it is a property of biospheres to optimize their use of raw material and free energy to control the planetary surface conditions at those most favourable for survival then this form of biosphere or an alien chemical one should be recognizable. Except by a purposeful act of camouflage any life system will reveal its presence through the chemical disequilibria caused by its contrivances.

Compounds now present in the Earth's atmosphere which might be seen by infrared analysis from afar are the chloro-fluoro-carbons: these are highly contrived products of chemical industry, made for their use as refrigerants and aerosol propellants. They could not have risen accidentally by inorganic chemistry and their presence would be indicative of either a biological life which had developed a chemical industry or alternatively an exobiology mechanically based. The concomitant evidence from the planet should help distinguish between these two life forms.

The greater part of this discussion has been concerned with the properties of planetary atmospheres. This is partly because more information is likely to be available about planetary atmospheres than about their surfaces and partly because the physical chemistry of low pressure gas mixtures is considerably easier to consider than that of mixtures including also the solid and liquid phases. But a view of a planet does provide information on such surface features as clouds, oceans, the albedo, the emissivity and the distribution of temperatures and chemical substances; these all can add weight to the sum of evidence concerning the presence or absence of life. Margulis & Lovelock (1974) discuss the devices a hypothetical planetary biosphere might use actively to maintain tolerable temperatures. For example, under conditions where the simple control of emissivity by greenhouse gases alone was not enough, the control of albedo or water evaporation might serve instead. The presence at the ocean surface of a bloom of light or of darkly pigmented micro organisms could serve the first purpose; the simultaneous production by these micro organisms of a suitable lipid might serve to control evaporation of water from the ocean surface. These are highly speculative suggestions and there is no evidence that they have been used in the Earth's past history. They are mentioned here as examples of hypothetical biospheric contrivances whose presence if discovered would add weight to the other evidence concerning life.

Summary and conclusions

This work started a decade ago, motivated by the need to design a life detection experiment for Mars which was not geocentric. Hopefully it was thought that such was the information intensity of life whatever its form might be, that enough entropy reduction for its recognition would spill over into the planetary environment. Inevitably it was necessary to draw upon information about the Earth, since it is the only planet we know with life. When the Earth was seen in this context it revealed an astonishing and unexpected degree of contrivance in what was then regarded as the non-living parts of the planet; the atmosphere, the crust and the oceans. There was more than merely a spill over of entropy reduction, it seemed as if these compartments were parts of the biosphere itself, not living, but bearing a relationship like that of a shell to the snail. By contrast what could be discovered of the other planets showed no signs of significant departure from the expectations of steady state inorganic chemistry. If future planetary explorations confirm the absence of life on the other planets of our solar system then the remote detection of life by telescope might be established as a method, at least for planets like the Earth. It may even be a general method of planetary life detection.

It may be some time before we can try these tests for life on the planets of other stars but in the meanwhile what started as an exercise in exobiology could become an expedition to discover the largest living creature on Earth, Gaia.

I am very grateful for the help and advice of my colleague S. R. Epton and I thank Shell Research Limited for financial support.

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Discussion

I. R. Kaplan (*Department of Geology, University of California, U.S.A.*). One has to be very careful about offering generalizations for life processes based only on disequilibrium conditions. We have two excellent examples of extraterrestrial material where non-equilibrium exists, but yet we are confident that no life exists at the point of origin of these samples.

The first case is in carbonaceous chondrites types I and II. There, epsomite ($MgSO_4.7H_2O$), magnetite, carbonate and other oxidized minerals coexist with reduced minerals such as troilite. Troilite represents the maximum reduction state for iron and sulphur and is rarely found under the oxidizing conditions prevailing on Earth. The other example is from the lunar surface. Here, in contrast with carbonaceous chondrites, conditions are very reducing. In fact the lunar surface is swept by protons from the solar wind. Metallic iron and troilite are stable and common mineral phases, yet there is some evidence that goethite may be present in small amounts in some samples.

An additional comment bears on the content of metabolites, either dissolved in the ocean or in the atmosphere. The content of ammonia, methane and especially hydrogen is extremely low. In fact, the latter is generally below all levels of detection. The fluxes of these metabolites give more accurate assessment of the relative intensity of the processes involved. However, when we come to search for life, either by direct or indirect means, on other planets or other solar systems, we will measure concentrations and not fluxes.