

hood of life, the entropy production of the planets is determined by the difference in the entropy between incident solar photons and reradiated thermal photons. Mass transport, which is necessary for life, is estimated in terms of atmospheric mixing for the various planets. A number of miscellaneous characteristics are also considered. Earth appears most favorable for life. Mars probably has primitive thermodynamic life in the form of crystal growth. Life on the other bodies in the solar system appears unlikely.

1. INTRODUCTION AND A THERMODYNAMIC DEFINITION OF LIFE

Research in exobiology to date has been limited to the assumption that life must be comprised of carbon compounds (e.g., Lederberg, 1960; Sagan, 1961; see also the excellent book *Extraterrestrial Life: An Anthology and Bibliography*, compiled by Shneour and Ottesen, 1966). Investigations concerning the origin of life have been largely limited to the consideration of the origin of certain carbon compounds such as amino acids (e.g., Fox, 1960; Haldane, 1954). The search for extraterrestrial life is to be largely limited to the search for certain carbon compounds, for example, optically active compounds (Stryer, 1968).

While this preoccupation with carbon chemistry is perhaps understandable in terms of life as it is ordinarily known on earth, it may not envision life in a context sufficiently broad to yield a proper estimate of what may actually be found on other planets. Present knowledge concerning extraterrestrial environments is largely limited to rough estimates of their thermodynamic properties. To estimate the likelihood of life existing in such environments should then involve an investigation of the thermodynamic role that life would play within these environments. In this

context the thermodynamic behavior of life becomes of paramount interest. For this reason it will be useful to define *life* here in terms of a few simple thermodynamic criteria. In particular, the property of *life* will be assigned to an object (or collection of objects) if:

1) it is an open thermodynamic system exchanging energy, compounds and radiation with its environment;

2) the elements it maintains internally have a lower entropy than these elements as originally found in the non-living environment; and

3) it creates or maintains internal states of low entropy by dissipating high utility energy to low utility energy.

These general thermodynamic properties are clearly applicable to ordinary metabolizing life as it is found on earth. Homotrophic organisms reduce the entropy of compounds taken directly from the environment* by dissipating high utility solar energy. Heterotrophic organisms increase the entropy of compounds returned to the environment and dissipate energy in order to maintain an internal state of low entropy.

The thermodynamic definition of *life* not only appears to have merit in the present investigation, it also appears to have merit in a more general and fundamental sense. It may be readily appreciated that any definition of life should include at least these thermodynamic properties listed above (either explicitly or implicitly). This thermodynamic definition of life appears to be about as general as possible without losing the

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problems which might not be so readily attained when more restrictive definitions are adopted.

In some contexts it may be of value to define *life* in a narrower sense. For example, a geneticist would probably find it of value to choose the added requirement that a *living* object be one that is capable of self-replication. A physiological chemist might find it of value to append some dynamic chemical requirements to the definition. In order to stress the distinction between the many possible specialized definitions of *life* from the general thermodynamic definition proposed here, the two words *thermodynamic life* will be introduced in place of the single word *life*.

The three defining thermodynamic criteria presented above include objects (or collections of objects) that are not ordinarily regarded as living. For example, a salt crystal which is growing in a saturated solution satisfies these criteria. It is an open thermodynamic system; the ordered arrays of ions in the crystal represent a reduction in the entropy of these ions as compared with their disordered state in solution; and this reduction of entropy is achieved by a dissipation of energy. Consequently, such a growing salt crystal will be regarded here as one of the simplest forms of thermodynamic life. In support of this classification of growing crystals a number of points may be made: Electron microscopes are revealing the fact that ordinary life possesses many essentially crystalline features, organelles possessing orderly arrays of complex molecules (e.g., Fischman and Weinbaum, 1967), which suggests that ordinary life may be basically crystalline in nature. Crystal growth, like any form of thermodynamic life, can play a significant role in the thermodynamics of an ecological system (e.g., the crystallization of ice on earth). Crystals, like any form of thermodynamic life, can only grow in an environment which permits entropy-reducing processes to occur. It is possible for crystal growth to compete with more advanced life forms for available energy and compounds. Crystals may be deposited as low entropic ore bodies which may be of value to more advanced life forms; thus, growing crystals may be regarded as homotrophic organisms which provide food for heterotrophic organisms. Under ordinary conditions it appears that crystals, like most life, cannot be spontaneously generated; a seed, nucleus, germ, or parent crystal

German shell was imported into the United States that it became possible to manufacture crystalline TNT. Today there are enough nuclei in the air at all times to produce crystalline TNT with ease. All crystal growth, as all living processes on earth, is achieved directly or indirectly through the action of sunlight (neglecting the small effect of the earth's fossil heat). It is possible to speculate that the earliest advanced life forms arose by competitive crystallization (and/or polymerization) of amino acids.

Another reason for considering a broad thermodynamic concept of life is the fact that thermodynamic life not based upon carbon chemistry is readily conceivable. For example, it is relatively easy to conceptually extrapolate from man's present day technology to a technology where all processes (including the control processes presently performed by man) could be carried out by robots and machines without life involving carbon chemistry being in any way necessarily involved (e.g., solar energy might be directly utilized). Such machine life would be restricted and bounded by the same thermodynamic limitations as ordinary carbon life today. While criteria 1) and 2) above would be expected to apply to each individual machine, criterion 3) would in general be expected to refer only to some large collection of machines taken together; i.e., a particular machine might create order in a large collection of machines but not necessarily within the body of the particular machine itself. If machines are included with thermodynamic living organisms, coexisting and competing with man (the relationship being frequently symbiotic), then a theoretical structure is available for considering the thermodynamic behavior of ecological systems involving both man and machines. As an indication of the importance of such problems, it may be noted that the burning of fossil fuels (the food for machines) has accounted for a 13% increase in the CO₂ content of the atmosphere in the last 50 years (Bray, 1959).

The thermodynamic definition of life proposed here is a dynamic definition requiring processes to take place as functions of time, so that some objects with some of the static properties ordinarily associated with *life* will not be *thermodynamically alive*. For example, a frozen amoeba, being a closed thermodynamic system, is not thermodynamically alive according to criterion

secondary degenerative processes which continue and which make the system thermodynamically open) but in addition does not ordinarily have the potential of life.

The frequently chosen defining criterion that life be comprised of self-replicating objects (e.g., Miller, 1957), while clearly useful in some contexts, is not adopted here, because it is not directly related to thermodynamic principles. Like motility, self-replication appears to be a common feature of thermodynamic life, but not an essential thermodynamic feature. Viruses, which are thermodynamically alive, for example, do not self-replicate; even though they do provide the blueprint which the factory cell uses to turn out more virus particles. Automobiles, as members of a viable thermodynamic system, are also not self-replicating; the blueprints for their manufacture are retained in the factory. It is relatively easy to conceive of a system of objects carrying on all possible (thermodynamic) living processes, but without each individual self-replicating (the entire system of objects would, of course, have to be replicated). It may be noted that under ordinary conditions in nature crystals do grow from seed crystals and, thus, do ordinarily self-replicate.

It is frequently claimed that carbon chemistry is requisite for life because only carbon chemistry can provide the requisite complexity. But ordinary life forms are comprised of compounds of low entropy which were derived from compounds of higher entropy in the environment (in agreement with the general thermodynamic criterion 2) adopted here). This means that life produces simpler systems rather than more complex systems, where the term *complex* as used here is unambiguously defined as follows: Thermodynamically the microstate of a system is specified when the position and momenta of all of the atoms comprising the system are specified. The greater the thermodynamic order, the lower the entropy, and the fewer the statements needed to specify the microstate of the system. For example, the microstate of a pure crystal may be specified by the lattice spacings, the crystal orientation and the position of the crystal, the position of each of the component atoms being thereby specified (neglecting small oscillations and defects). If the same atoms were in a gaseous phase the position and momenta of each atom

oms in the gaseous phase; the gaseous phase is more *complex*. In general a lower entropic state is thermodynamically simpler, and a higher entropic state is more *complex*. The assumption that life requires a complex chemistry, thus appears to be contrary to the actual thermodynamic behavior of living systems.

The three criteria chosen above to define life, being based upon the dynamic behavior of objects instead of static characteristics such as chemical structure and morphology, yield some insight into how man might need to adjust to alien life quite independent of the detailed nature of the alien life. Thus, it may be assumed that man will have to compete for the available high utility energy. In general alien life should be regarded as hostile until man can prove himself capable of competing for the available energy.

2. UTILITY OF ENERGY

Since energy is neither created nor destroyed (it is conserved), the value of energy to an organism is in the ability to convert the energy from a state of high utility to a state of low utility. If it is assumed that mechanical work is the form of energy with the maximum utility, then the utility of energy n may be defined explicitly as that fraction of the energy available which in principle could be converted (at a finite rate) into mechanical work; thus,

$$n = (\text{work out})/(\text{energy in}). \quad (1)$$

For example, thermal energy has a utility which is necessarily less than that of a Carnot heat engine operating between the hot source and a cold sink. Mechanically stored energy, such as in a raised weight or in a stretched spring, has a utility of essentially unity. The utility of chemical energy available in an isothermal isobaric process may be taken as at most

$$n = -(dA/dH)_{T, p}, \quad (2)$$

where A is the Helmholtz work function, H is the enthalpy, T is the Kelvin temperature, and p is the pressure.

In general the concept of utility of energy has meaning only within the limited context in which energy is, in fact, being utilized.

living organisms is their ability to create and maintain an internal state of entropy lower than the entropy of the same elements in the non-living environment (Schroedinger, 1956; Asimov, 1962; Pardee and Ingraham, 1960). Since most physical systems in nature when left to themselves proceed with time toward a state of thermodynamic disorder or high entropy, only very special environmental conditions are compatible with the thermodynamic ordering behavior of living systems. It is evidently only by continual dissipation of energy of high utility to low utility that living organisms are able to create and maintain their internal states of low entropy. For example, green plants dissipate the high utility solar energy by converting it into low utility thermal energy (neglecting the small fraction which becomes stored as chemical energy). In this way green plants convert gaseous CO₂ and liquid H₂O, which have high entropy, into solid cellulose which has low entropy. They also reduce the entropy of the atmosphere when the 0.033% of CO₂ is separated from the remaining constituents in the atmosphere (the entropy of mixing).

The second law of thermodynamics (Sears, 1953) states that the net change of entropy of the universe for a given process never decreases,

$$dS(\text{universe}) \geq 0, \quad (3)$$

where S is the entropy and the equality holds for reversible (idealized) processes only. In order for living organisms to decrease the entropy of the materials taken from the environment and included within their bodies, the remainder of the universe must suffer a correspondingly larger increase in entropy; from eq. (3) this means

$$(-dS)(\text{internal to organism}) \leq dS(\text{universe external to organism}). \quad (4)$$

An important conclusion may be drawn from eq. (4): the larger the right side, the larger the left side can be potentially. Thus, the larger the increase in the entropy external to the organism, the greater the potential the organism has for creating thermodynamic order internally. Ordering processes, including life, can only arise in environments that are increasing the entropy of the universe with time. The environment that produces the greater time rate of increase in the

environment to support life, but it is not a sufficient condition. The word is used in precisely the same sense as the word *potential* in *potential energy*. For example, a boulder resting on a hillside has the *potential* of doing work when lowered into the valley below; but it may never be lowered into the valley; so that the *potential* of doing work, while a necessary condition, is not a sufficient condition for the work to be actually performed.

4. ENTROPY PRODUCTION OF THE PLANETS

A closed system cannot increase the entropy of the universe indefinitely, so that a closed system cannot support life indefinitely. The surface of a planet is an open thermodynamic system which is supplied with high utility solar energy which is reradiated as low utility thermal energy. The surface of a planet increases the entropy of the universe at a steady rate. Radiant energy of the amount dQ leaving the sun carries an entropy dQ/T_1 where $T_1 = 6000^\circ\text{K}$ is the effective surface temperature of the sun (Epstein, 1937). If this radiant energy dQ is absorbed by the surface of a planet an equivalent amount of energy must be reradiated (or transported away by convection) in order for the surface of the planet to maintain thermal equilibrium. The thermal energy reradiated (or transported away by convection) will be at the temperature T_2 of the planet's surface and will carry an entropy dQ/T_2 . The surface of the planet, thus converts radiant energy from the sun carrying entropy of the amount dQ/T_1 to thermal energy carrying an amount of entropy dQ/T_2 . The net entropy production (net increase in the entropy of the universe per unit time) created by the surface of the planet is then

$$\frac{dS}{dt} = \frac{dQ}{dt} \left(\frac{1}{T_2} - \frac{1}{T_1} \right). \quad (5)$$

Since the surface of a planet increases the entropy of the universe with time (eq. (5)), the surface of a planet has the potential of becoming more ordered with time. In particular, writing the second law, eq. (3), in the form

place depends upon the rate of diffusion processes in local regions. The rate of diffusion is indicated by the diffusivity or diffusion coefficient (Longworth, 1957). The diffusivity of molecules through solids is extremely small, being generally much less than one hundredth of the diffusivity of molecules through a liquid solvent. The diffusivity of molecules through a gas is about 10^5 times greater than through a liquid solvent. It thus appears that ordering processes would be achieved most rapidly in a gaseous phase. On earth both gaseous and liquid diffusion are important, liquid diffusion being particularly important for those molecules which are never found in the gaseous phase.

Since the diffusivity increases with temperature, planets with a higher temperature (all other effects of temperature being assumed equivalent) would tend to be more favorable for the ordering processes of life.

A micro-organism (or crystal) can assimilate molecules at a rate which is dependent upon the concentration gradient at the surface of the micro-organism (or crystal). If there were no transport process other than diffusion, the concentration gradient would eventually go to zero monotonically with time and all entropy-reducing processes would eventually have to cease. Only macroscopic flow and mixing can revitalize the medium by recreating a non-zero concentration gradient at the surface of the micro-organism (or crystal). Since macroscopic flow and mixing of solids is not possible, ordering processes will eventually cease on a planet without gases or liquids, and (sessile) life will therefore not exist on such planets.

The amount of macroscopic mixing of the atmosphere of a planet indicates the degree to which ordering processes can continue. The amount of mixing may be estimated by observing the motion of clouds. Convection and turbulence may also be inferred if a greenhouse effect traps solar energy next to the solid surface, thereby requiring convection of hot gases to transport the thermal energy to higher altitudes where it may be reradiated into space. The degree of such mass transport is indicated qualitatively in table I for the various planets.

The motion of living organisms through a gas or liquid or over a solid surface achieves the same effect as the macroscopic transport of ma-

pected as a common evolutionary development for advanced life forms.

Besides motility, life (on earth) also achieves macroscopic transport of matter by the use of special mass moving organs such as cilia, gullets, flagella, gills, lungs and hearts. It would seem, however, that without other types of macroscopic mass transport also being present that such specialized organs would eventually deplete the desired molecules in the neighborhood of a sessile organism and that life would then cease.

6. MISCELLANEOUS CRITERIA FOR ESTIMATING THE LIKELIHOOD OF LIFE ON THE PLANETS

Since life as viewed through the electron microscope appears to have many crystalline features and is in a state of relatively low entropy, the environment which can support life should admit the possibility of solids existing. The outer layer of the sun effects a tremendous entropy production, thermal energy being degraded from a temperature of about two million degrees in the interior to a temperature of only six thousand degrees at the surface. This provides a tremendous potential for ordering processes to occur; but since no solids can be present (unless perhaps the interior of sun spots is much cooler than is presently assumed) at the elevated temperatures of the sun, no life can exist.

Since high utility energy (solar energy) must be available in order for entropy reducing processes to yield crystal type depositions, it appears that sunlight has to illuminate the solid surface of a planet in order for life to exist. There might be a slight possibility that life could exist as solid particles floating in the atmosphere as a cloud; then life could exist without the solid surface of the planet being illuminated. In this case life would have to be formed only from the normal constituents of the atmosphere and would have to be of a low density.

Life, evolving toward an optimal utilization of sunlight, would tend to reduce the albedo of the surface of a planet in order to increase the entropy production. For example, the albedo of a forested area on the earth's surface is in general less than that of desert sand. Thus, a lower albedo is more suggestive of life being present.

where the increase in the entropy of the universe external to the surface of the planet is given by eq. (5), it becomes apparent that the entropy of the surface of a planet has the potential of decreasing with time.

Examining the earth about us there are many indications that the earth is, in fact, becoming more ordered with geologic time (see Gutenberg, 1951). There was a vast decrease in entropy when the earth condensed out of the primordial gas cloud. The separation of the compounds forming the crust, mantle and core represents another vast decrease in entropy. The lithosphere appears to be separated into highly differentiated deposits of compounds compared with the relatively homogeneous underlying basalt. These separate deposits of limestone, salt, clay, iron oxide, coal, etc. represent further decreases in the entropy.

Assuming a limited range for ordinary mass transport processes, the total entropy production taken over the entire surface of a planet is not as significant a measure of the potential for life as the entropy production per unit area during the day. A detailed computation of the entropy production per unit area would take into account the variation of temperature and incident solar energy flux over the illuminated hemisphere of the planet. Here, however, it will be sufficient to choose a single average daytime surface tem-

unit area of the surface of a planet is given by

$$\frac{dS}{Adt} = \frac{R r_e^2}{2r^2} (1-A) \left(\frac{1}{T_2} - \frac{1}{T_1} \right), \quad (7)$$

where r is the mean distance of the planet from the sun and r_e is the mean distance of the earth from the sun (the astronomical unit). The 2 in the denominator arises from the fact that the area of the hemisphere is twice the area of the circle intercepting sunlight. Numerical results are presented in table 1.

5. TRANSPORT MECHANISMS* AND THE ABILITY OF AN ENVIRONMENT TO SUPPORT LIFE

Entropy-reducing processes, such as required for life, require the transport of selected molecules from scattered locations to a single location where they are arranged into an orderly array. Transport mechanisms must therefore be present which can move the selected molecules from place to place. In local (or microscopic)

The transport mechanisms referred to here are general mass transport mechanisms (primarily in the environment); they do not refer to the transport of material across a cell membrane.

Table 1
Characteristics of the planets which give some indication of the likelihood of life.

Body	Dist. from sun 10^{13} (cm)	Surface temp. $^{\circ}$ K	Albedo**	Entropy production area $^{-1}$ (erg sec $^{-1}$ cm $^{-2}$ $^{\circ}$ K $^{-1}$)	Atmospheric mixing	Liquid or gas present	Solid surface illuminated	Surface variegated	Temporal changes
Mercury	0.379	429	0.056	6360	none	neither	yes	yes	none
Venus	1.081	480	0.78	481	large	gas	?	no?	cloud
Earth	1.495	280	0.36	1470	some	gas, l	yes	yes	seasonal and cloud
Moon	1.495	400	0.067	1520	none	neither	yes	yes	rare
Mars	2.278	220	0.16	1110	small	gas	yes	yes	seasonal and cloud
Ceres	4.186	240	0.06	355	none	neither	yes	yes	none
Jupiter	7.778	140	0.73	48.6	large	gas, l	no?	yes?	cloud
Saturn	14.26	100	0.78	18.1	slight?	gas, l	no	no	slight?
Uranus	28.68	64	0.93	2.05	none	gas, l	no	no	none
Neptune	44.94	51	0.84	2.40	none	gas, l	no	no	none
Pluto	59.08	63	0.14	6.04	none	neither	yes	yes	none

* Pettit, 1961; Sinton, 1961; Maier, 1961.

** Harris, 1961.

particularize the defining criteria of life to such a degree that life, as so defined, could only exist on the earth, it does not appear that this is the case in the present analysis. The very simple thermodynamic criteria used to define life are also the criteria for ordinary crystal growth. It is significant that the earth appears to be the best environment for crystal growth. The earth thus probably provides the greatest opportunity for finding ore deposits.

The present paper is limited to the consideration of life which might have evolved from the most primitive beginnings on the surface of a planet. The problem of where to find sophisticated life with advanced technology has not been considered here.

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