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BIOLOGICAL GENERALIZATIONS AND THE SEARCH FOR EXTRATERRESTRIAL LIFE

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D. B. Hoffman
A. N. Kontaratos

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ABSTRACT

This study is an attempt to provide a framework for a systematic approach to the search for extraterrestrial life. Possible universal attributes of life are derived from inferences based on the functional characteristics, the material building blocks, the levels of organization and the origin and evolution of terrestrial life. These generalizations are divided into hereditary, morphological, metabolic and ecological categories and, like other scientific hypotheses, are subject to refinement and change.

Some limitations of operational approaches to the search for extraterrestrial life are identified. Working assumptions are then developed to allow definition of appropriate tests within these limitations. This information is in turn used to establish criteria barring the existence of life, criteria suggesting the possible existence of life and criteria confirming the existence of life. Finally, an overall program development sequence for the biological exploration of the solar system is presented.

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INTRODUCTION

Basic questions about life, its cosmic distribution and its origin are not new. For centuries biologists have been attempting to define life without notable success. Efforts have also been made to explain the origin of life in mechanistic chemical terms. It has been shown that molecules of basic biological importance can be synthesized by natural processes under laboratory conditions simulating an assumed primitive atmosphere. Yet, despite this progress, the nature and origin of life still elude us.

Space exploration offers the opportunity to search for life and life-related molecules on neighboring planets. To biology the importance of such a search is invaluable because biological studies have been limited to only one type of life--that found on Earth. The discovery and characterization of extraterrestrial life forms, life precursors or evidence of either is significant both for giving the perspective to biology already available to the other physical sciences and for improving our limited theoretical concepts concerning the nature of life.

In this report, written for the non-biologist as well as the biologist, an attempt is made to provide a framework for a systematic approach to the search for extraterrestrial life. Possible universal attributes of life are derived from consideration of terrestrial life. Criteria for the detection of life are obtained from these generalizations, and appropriate strategies for the search for extraterrestrial life are briefly described.

II. GENERAL PRINCIPLES OF TERRESTRIAL LIFE

A. On Definitions of Life

Biologists strive to define and understand life. Yet, even today they have not succeeded in its precise definition. This may partly result from the limited capability to separate that which is necessary to life from that which is ancillary, and to recognize a clear demarcation between animate and inanimate matter. Because of such difficulties, there is a tendency to explain life in terms of observable attributes which provide a description rather than a definition of life. Some biologists now believe that the living state is a consequence of molecular interactions, and may be explainable in structural and chemical terms. Others believe that it is ascribable to the complexity of interacting multi-linked sub-systems.

Attempted definitions of life are generally vague and relatively non-quantitative. For example, life could be defined as a local decrease in entropy sustained by self-controlled dynamic processes among reacting molecules in an enclosed system thermodynamically open to interaction with the environment and directed towards maintaining and propagating its local structural integrity.

Such a definition does not offer any substantial operational aid to the biologist interested in the recognition of life, especially life present on another planet. To provide an answer, one is forced to resort to drawing inferences based on the observable attributes, the material building blocks, the levels of organization and the origin and evolution of terrestrial life. These are the subjects of the rest of this chapter.

B. Attributes of Life

The attempt to specify universal properties for all life forms is limited by our earthbound experience. Difficulties exist even in recognizing life by terrestrial criteria because the more entities one accepts as living, the more numerous and less rigorous become the properties that can be enumerated. Inaccuracies may thus result from any attempt to derive a general description of life in terms of specific observable characteristics.

Sets of gross attributes of life generally found in textbooks usually include growth, movement, irritability (response to stimuli), reproduction and metabolism. Interestingly enough, many characteristics of life listed as independent actually depend upon metabolism. In fact, metabolism is necessary for all life processes. Only death can be described as a state lacking controlled metabolism. A grouping of commonly stated life attributes into independent classification of primary and derived (secondary and tertiary) characteristics is given in Table I.

From this table of properties, basic statements can be made which can be accepted as necessary (although perhaps not sufficient) attributes of a molecular system in order for it to be called "alive." These are: (1) the ability of such a molecular aggregate to transfer and transform energy in some specific way, (2) its ability to memorize this process, (3) its ability to transfer this information to other similarly derived units which it can construct, and (4) its capacity to mutate to a new genetically stable form.

Usually it is not necessary to apply the above criteria for the recognition of terrestrial life forms. Experience allows us to easily distinguish the living from the non-living. However, difficulties do exist at the animate-inanimate borderline (e.g., the controversy concerning whether or not a virus particle is alive) and, therefore, recognition of extraterrestrial life, if any, could prove difficult.

C. The Building Blocks of Life

All terrestrial life forms ranging from viruses to humans are composed of only 21 elements. These can be classified in three groups with respect to their abundance in animate matter:

MAJOR ELEMENTS:

H, C, N and O

TRACE ELEMENTS:

Na, Mg, K, Ca, P, S and Cl

ULTRA TRACE ELEMENTS:

V, Mn, Fe, Co, Cu, Zn, B, Si, Mo and I.

The principal organic substances of life found in all living organisms are carbohydrates, lipids (fats), proteins, nucleic acids, and co-enzymes including vitamins and energy transfer and storage compounds. Each class has specific functions. Carbohydrates are classified in three main groups: monosaccharides (one unit), oligosaccharides (two to nine connected units), and polysaccharides (polymers of hundreds to thousands of monosaccharides). Fats (or lipids) consist of fatty acids joined to glycerol. The principal function of carbohydrates and fats is to store energy and serve as fuel. In most cells, the great majority of lipids is compounded with proteins (lipoproteins) to form structural sub-units including the apparently ubiquitous lipoprotein membrane. Water is ubiquitous in terrestrial biology serving as a solvent for the organic biological chemistry.

Proteins, which are polymers of amino acids, are the basic functional and structural macromolecules of the cell. They form parts of membranes, various organelles, etc., and also serve as enzymes or biological catalysts responsible for the controlled regulation of biochemical reactions. Amino acids also serve as energy sources. A protein molecule consists of hundreds of amino acids linked together in a chain. While some eighty amino acids are presently known, only twenty-two take part in the construction of proteins. These twenty-two amino acids are found in all terrestrial species from viruses to humans and like the twenty-six letters of the alphabet, can be arranged in countless sequences that determine their various functions. Each protein is formed from a unique sequence of amino acids. The sequence in turn determines the three-dimensional structure of the protein molecule through intramolecular forces and interaction with the immediate environment. This "tertiary structure" is responsible for the activity of the protein, either as an enzyme or as a structural unit.

Nucleic acids are of two kinds--DNA (deoxyribonucleic acid) and RNA (ribonucleic acid). DNA is the repository of encoded instructions for functioning and continuity. RNA carries the instructions from the DNA to the sites of protein synthesis (ribosomes), and is important at all levels of protein biosynthesis. Amino acids are hooked together at the ribosomes to conform to the DNA pattern as reflected by the RNA messengers, and form the proteins.

DNA is a double-stranded polymer built of a sequence of dimer units arranged in a staircase stacked configuration. It stores information in structural form and is the embodiment of the genetic code. The dimer units are chosen from only four bases (with a few exceptions)--adenine with guanine (purines) and thymidine with cytosine (pyrimidines). These are linked to deoxyribose sugar and phosphate backbones and paired into dimers of adenosine-thymidine, guanidine-cytidine phosphates, respectively. The sequence of three such dimers has been shown to specify or code an amino acid, the monomer unit of the protein. This code (both physically and programmatically) is apparently identical for all terrestrial life. The linear arrangement of dimers gives rise to the immense diversity of biological species.

RNA is similar to DNA except that the sugar moiety is ribose and uridine is substituted for thymidine. In addition to its use as the basic genetic material in a few plant viruses, RNA serves as a translating agent, and is responsible for several intermediary steps in the transcription and construction of proteins. It is found in both single and double stranded forms. Again the same units of ribonucleosides are found in all species from viruses to man.

A final group of important organic compounds includes miscellaneous small biologically active molecules. This group includes the vitamins, which serve mainly to assist the enzymes as co-enzymes, and serve important roles in oxidation and reduction of compounds and in the electron transport chain in which outside energy is brought into the cell and put into biologically useful form. In addition, several molecules such as adenosine-tri-phosphate (ATP) and a few other compounds which are energy storage and transfer units, and porphyrins, which are complex molecules active in electron and oxygen transport, are included in this group.

As presently understood, life is a manifestation of certain molecular aggregates, mainly nucleic acids and proteins, and their controlled interactions. As already discussed, the nucleic acids are the ultimate self-replicating and mutable substances that carry the genetic code of inheritance. This code consists at least of information concerned with the construction of proteins. The proteins include the enzymes which permit and specify the complex chemistry of organisms, including the production of the precursors needed for the synthesis of all biological molecules. Thus, the nucleic acids and the proteins form an interlocking-interdependent system and whatever is unique about living matter may be apparently inherent in this system (Ref. 1).

It also appears that the information required to build discernable biological structures (tertiary structure) is contained in the primary sequence of the constituent monomers. That is, the polymers of nucleic acids and proteins contain within their linear chemical sequence the necessary information to give rise to the helices (secondary structure) and to fold this structure on itself in a unique way (tertiary structure). For proteins, for example, this unique folding leads to an extremely complicated and precise three-dimensional structure which establishes the specificity of enzymatic functioning.

Because the structural specificity of inherently asymmetric polymers controls life processes, all organisms discriminate among optical isomers* as far as the absorption and utilization of metabolites (raw material) is concerned. This is a property found naturally only in processes associated with life.

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* A pair of chemically identical but non-superimposable compounds (mirror images) that rotate polarized light in opposite directions.

In summary, life on Earth is based on a carbon chemistry with water as the solvent. Additionally, of all the billions of organic compounds that are possible, the basic building blocks of animate matter (millions of species) consist of less than fifty organic monomers. A generous estimate of the types of biological compounds making up the entire terrestrial biomass is less than 1500 (Ref. 2).

D. Levels of Organization

Organization is found everywhere in biology. The molecular subcellular organization has been discussed above in terms of the universal sets of functionally specific molecules. These participate, undergo and control metabolism through an elaborate biochemical network. It is also of interest to note that at each level of organization, biological function cannot be deduced from knowledge of the properties of all individual constituents considered separately. For example, the catalytic function of an enzyme cannot be deduced from the properties of its individual amino acids.

The cell is generally recognized as the fundamental living unit and the first major level of biological organization and integration. It interacts with the environment through a highly structured membrane of selective permeability and possesses highly organized inclusions known as organelles (nucleus, mitochondria, ribosomes, etc.).

Although cells have similar components, they differ greatly in appearance. For example, cell diameters vary from about 1000 Å to 1 mm in diameter. Maximum size appears to be limited by the square/cube law. In other words, the quantity of nutrients a cell requires is proportional to its volume, hence to the cube of its size; but the absorption of nutritive substances is a surface diffusion process, hence proportional to the square of its size. Consequently, the bigger the cell size, the smaller the volume-to-surface ratio, the harder to satisfy metabolic demands. Factors placing a lower limit on cell size are not clearly understood but simple theoretical considerations paired with heuristic generalizations have indicated that 400 Å is an approximate lower bound on the diameter of an autonomous self-replicating unit with terrestrial life characteristics (Ref. 2).

The cell can be viewed as an integrated entity, spatially and functionally organized to carry out the necessary processes of life. Control of these processes is maintained by a variety of chemical feedback mechanisms.

An aggregate of similar cells joined to perform a specialized function is a tissue. Tissues combine to form organs which are special purpose bodies.

A self-sustained ensemble of interacting cells, tissues and organs is known as an organism and can be accepted as the second major level of biological organization.

There appears to be a tendency of animate matter to evolve towards higher complexity. Unicellular organisms can survive environmental changes because they continually maintain a large pool of genetic variants within any population, by means of their fast growth and replication rates. These variants provide the species with adaptability because they include types which can survive, grow, and reproduce better than the present dominant type when environmental change occurs. The creation of complex organisms requires differentiation into specialized cell types and the establishment of an organismic hierarchy to coordinate and control the function of these different cell types. Through specialization, complexity offers an alternative method of dealing with environmental change not requiring high rates of genetic adaptability. Complex organisms (among which are included larger organisms since complexity is a natural result of increased size) can create and maintain a constant internal environment. This affords protection of individual internal components and shielding of the hereditary material from externally induced changes. In this way genetic stability is better preserved.

Collections of organisms form populations. A self-sufficient aggregate of populations interacting with themselves and the environment is collectively called an ecosystem and is recognized as the third major level of biological organization.

Within any ecosystem, the struggle for existence is tantamount to the struggle for available energy. Green plants are the primary producers in the economy of nature. Radiant energy is absorbed and utilized by the photosynthetic organisms to manufacture organic compounds. These organic compounds in turn furnish the energy required by most non-photosynthetic forms of life. The dependence of the ecosystem upon the sun as the primary source of energy is shown schematically in Figure 1.

Study of the interactions among populations within an ecosystem discloses that a more detailed diagram of the food relationships among its members produces a sort of web. Since a consumer is seldom confined to a single source of food, the complexity of the ecological web increases rapidly with increasing numbers of heterogeneous populations. Increased web complexity implies, however, increased ecological stability, because there is less dependency upon the fluctuations of any particular secondary energy source. Variety at the population level is, therefore, a strategy to preserve the stability of the ecosystem.

Higher levels of organization within the ecosystem do not replace lower organizations; complex organisms depend upon simpler ones to provide their energy requirements. In a sense a division of labor occurs in which some organisms provide others, usually higher animals, with preformed materials, thus freeing their cells for other duties. In return, the higher animals' waste products provide nutrients for simpler organisms. Small organisms are valuable as specific decomposers, a variety of which can be available at any place or time. Additionally, they can fill a variety of ecological niches within a small space and help to assure ecological closure. They can form the vanguard of biotic invasion of non-organic areas inaccessible to larger forms. Because of their large numbers, fast growth and division rates, and metabolic potential, they provide a variety of available mutations which can respond quickly to environmental changes or fluctuations and help stabilize the biosphere. For this same reason they are on the frontier of experimentation with new energy sources and new biochemical pathways. As nature is profligate, most of them will perish, but some will succeed. They provide the mechanism for continuous probing necessary to open new ecological niches and maximize the occupancy of the available environment.

The totality of ecosystems on Earth forms the biosphere. Within the biosphere, each ecosystem represents a controlled aggregate of interacting populations which is stable, or homeostatic, to environmental fluctuations.

E. Biological Efficiency

Efficiency is the key to success at all life levels. In the ecological sense, this means to make optimal use of the available resources and maximum occupancy of the available environment. Each species fits into a particular ecological niche, which is defined as the totality of all the requirements necessary for the organism's life. When overcrowding occurs, either the less efficient competitor must succeed in establishing a new niche in which he is the most efficient organism, or he is eliminated by better adapted competitors. This is a driving force in speciation, and possibly evolution. An example of the efficiencies at the ecological level is the principle of optimum use of available space. This is demonstrated most strikingly by diurnal and nocturnal species which can occupy the same ecological niche, with the exception of sleeping period, and thus use this available living space more fully.

Another example of efficiency optimization has been described with bacterial populations which differ genetically in only one gene. Enzymes which are only occasionally needed can be manufactured on command through a process called enzyme induction in normal (wild type) strains. Mutants which have lost this ability but make the enzyme continuously are known as constitutive mutants. The constitutive mutants are favored only when there is a constant food supply present. Since the cell cannot afford to manufacture a large number of useless enzymes, the wild type is favored in all other cases. In order to obtain the best efficiency, the repression of induction should take place as near to the beginning of the biosynthetic pathway as possible. This would eliminate many intermediates and reactions which are only necessary when the end product is desired. As an example, the amino acid arginine at an appropriate concentration blocks the synthesis of all enzymes involved in the chain of arginine biosynthesis without blocking any other pathway.

An efficiency mechanism also works in the selection by an organism of the energy source to be used when more than one is available. Given the choice of two energy sources, A and B, where A can yield more energy than B, bacteria will choose to use compound A until it is exhausted before using compound B. In this phenomenon called diauxic or diphasic growth, the organism strives to achieve maximal benefit from the environment by not using available but less optimal energy extracting biochemical pathways.

Another facet of biological efficiency is the utilization of identical chemical subunits by all terrestrial species. Derived benefits include maximal reuse of biological materials, symbiosis, mutualism, etc. This has many ramifications, including evolution of similar biochemical pathways and the use of the same chemical intermediates. In general, the optimization of efficiency may be a general biological principle, and appears to be demonstrated in many ways in terrestrial biology.

F. Life and Energy

Life is a dynamic state in which energy is continuously utilized for physical (motility, irritability) and physiological (self-repair, growth, reproduction) activities. Viewed thermodynamically, life is a phenomenon of intense local ordering (local decrease in entropy), which is self-directing, self-propagating and ultimately dependent upon the utilization of solar energy. Radiant energy is absorbed and utilized to manufacture organic compounds by photosynthetic organisms, principally green plants. These organic compounds in turn furnish the energy required by most non-photosynthetic forms of life. Basic principles of ecology state that life is characterized by both a one-way energy flow from a stellar source to a celestial sink and a circulatory flow of materials. It is this flow of energy through the system which makes life go, and not just energy per se (Ref. 3). Thus, any interference with the energy flow circuit can have profound implications for life.

The dependence of the ecosystem upon the sun as the primary source of energy is shown schematically in Figure 1. It is important to recognize, however, that not all components of the ecosystem depend, either directly or indirectly, on radiant energy for survival. Some microorganisms exist which are specialized in manufacturing organic compounds by extracting energy from oxidizable inorganic substrates. Whether or not they are diversified enough to form a closed ecology among themselves is open to question. They do interact ecologically by providing materials for other organisms and utilizing inorganic waste products.

Figure 1 also depicts the turnover of building blocks that enter into the composition of living matter. Every biologically important element (either from the soil or the atmosphere) can be considered to pass through a continuous cycle from the nonliving environment to living matter and back to the nonliving environment.

Living organisms are affected by their environment and its fluctuations. However, it is also true that they change the environment through biochemical transformations and a local increase in the biomass (growth and reproduction). In the aggregate the biomass constitutes a critically important contributory factor to geochemical, atmospheric and even climatic changes.

G. Control in Biology

Biological interactions at all levels in the biological hierarchy are controlled interactions. Biological processes as control systems have been the subject of relatively recent investigations, and are discussed at length in References 4, 5, 6 and 7. The development of cybernetics itself has been coupled directly with the study of biological control systems.

Biological systems are goal-oriented. The goal of the organism, for example, is survival and reproduction--to ensure species continuity. Control is necessary in biological systems because any goal-oriented system must be stabilized and function in an orderly progression towards goal achievement. As an example, the biochemical network within a cell is regulated by several different types of feedback mechanisms. DNA replication is generally controlled to remain synchronous with cell division. The physically disrupted cell, however, cannot regulate its life processes, even if its components are suspended in the same growth medium. In this "in vitro" system some biochemical processes can and do occur and experimenters can manipulate the system to produce some desired products. But the self-regulation and all that made the cell "alive" have disappeared. This indicates that life is more than just an aggregate of components.

Regulation is observable on all levels of biology. Physiology is the study of biological regulation from cell to organ to organism. The control is mediated by a variety of agents as simple as CO_2 and as complex as proteins. Other aspects of the organism which reveal control mechanisms include growth, development, motor activity, visual tracking, thermal homeostasis, voice control, swallowing, respiration rate, heart rate, biological rhythms, etc. Most of these control systems are sensitive to external as well as internal cues.

Regulation also appears in animal behavior, in animal societies, between populations, and between the entire plant and animal communities and the physical environment comprising an ecosystem. These phenomena have been studied and analyzed with varying degrees of sophistication. Although the particular mechanism differs from one case to another, they are all used to attempt to optimize the achievement of some goal. There may be several control elements exerting partial influence on the given process or component being regulated. These elements themselves may be the controlled component in another control loop. Additionally, the same component can be used in different regulatory systems with diverse goals.

In general, in biology it seems that functional complexity (the interaction of many goal-oriented sub-loops) may be the key to stability. This can be seen most clearly in the predator-prey relationships in ecology. Systems in which the components have been reduced to a few are highly unstable and result in extreme population fluctuations and concomitant biological waste and environmental destruction. Highly complex "webs" have much smaller individual fluctuations, and in the aggregate are relatively stable. The degree of complexity required to achieve stability is not known presently, and may depend on the particular case.

H. Life in Extreme Environments

Terrestrial organisms have been able to adapt to extreme environmental conditions and there is virtually no place on Earth where viable organisms cannot be found. Organisms have been found in Antarctica, on mountain tops, in the Dead Sea, at oceanic depths, and in deserts. Some environmental extremes at which terrestrial life can survive are given in Table II.

Various mechanisms of adaptation have been used for survival. These include water-eliminating mechanisms, water conserving biochemistries, thermal homeostasis, dehydration, dormancy, etc. Even under conditions in which life processes cannot be sustained, many organisms have developed methods of surviving in a dormant state until better conditions return. Bacterial spores which contain all the necessary information to generate viable bacteria represent the dormant state in some species. These spores are relatively dehydrated containing less than 30% water, and can withstand dry heat up to approximately their kindling point. They can also survive high radiation fluxes.

Experiments in which the Martian environment is simulated have shown that growth of bacteria, or at least viable dormancy, is possible even under the stress of daily freeze-thaw cycles (Ref. 9, 10, 11, 12, 13), which have often been used in laboratories to disrupt cells. In one such set of experiments, spores of B cereus germinated and grew vegetatively in earth atmosphere at pressures of 10, 40 and 98 mb. The cells were enclosed in tubes containing felsite/limonite soil (believed similar to Martian surface material), a small amount of organic medium and 8 to 9% moisture. Under similar conditions, but using an atmosphere of 100% CO_2, spore germination was inhibited, apparently by the CO_2. However, little if any loss in viability was observed for a period of at least 28 days (Ref. 9). The experimenters used average values of the physical parameters of Mars as determined by remote sensing techniques. Such values could be extremely misleading if there are local variations of any magnitude. Other assumptions such as the nature of the soil and amount of water could lead to incorrect conclusions. These experiments do not prove the existence of extraterrestrial life. They merely show that some form of terrestrial life might survive on Mars, that some degree of sterilization of spacecraft and components is essential, and that if life similar to simple terrestrial forms arose on Mars at some time, it could have adapted to the present austere conditions. They also indicate that if life exists on Mars, it does not necessarily have to be exotically different from its terrestrial counterpart.

The internal chemical solvent of life (such as water) may not necessarily be present in large quantities in the environment, since it could be chemically created internally. For example, water is released in the polycondensation of amino acids during protein formation. A solvent would have necessarily been present during evolution, however, serving to bring reactants together. A chemical solvent is also necessary for material transfer within the cell or organism as well as to participate and aid in chemical reactions. Water is well suited for a carbon biochemistry, because it can dissolve a wide range of substances but not the basic structural components. The properties of water which make it a good solvent are discussed in Reference 39.

Life is probably possible wherever the solvent can exist in the liquid state long enough for the basic metabolism to occur. Life most likely cannot exist when the solvent boiling point is exceeded markedly or for appreciable times because chemical disorganization and biological disruption occurs. Alternatively, if the solvent were in the solid state (e.g., ice) permanently, it would be useless for material transport.

Terrestrial life has adapted to arid regions such as deserts, but the greatest variety and abundance of organisms are found in moist soils. Apparently, a minimum solvent content is required for active life. Inert viable seeds and spores have water contents as low as 30%, while metabolizing organisms have water contents exceeding 50%. The organism interacts with the environment as an open system. Thus, the production of the solvent must equal the loss to the environment. This is a crucial requirement and implies that the solvent should be observable in the environment.

The temperature is another critical environmental factor. The thermal environment affects chemical reactivity, molecular stability and organism viability. The rate of biochemical reactions, for example, is approximated by the equation,

$$r = \frac{kT}{h} \exp\left(-\Delta F^{\pm}/RT\right)$$

where k is Boltzman's constant, h is Planck's constant, T is absolute temperature, R is the universal gas constant and $\Delta F^{\ddagger}$ is the activation free energy of the reaction. Interpreted in a most simple manner as an example, this relationship predicts that if the activation energy is 12000 cal/mol°K, a reaction which is completed in one second on Earth would require 10 seconds on Mars but only 10^{-3} second on Venus, due only to local temperature differences.

Since all materials degrade at high enough temperatures, any system of life must be limited at least to an upper temperature bound. Low temperatures need not be a bar to life as long as the chilling does not involve structural damage to cells or tissues. A state of dormancy may be simply induced since the stability of biological molecules increases and the speed of reaction decreases with falling temperature.

Terrestrial organisms seem capable of surviving temperatures ranging from -270°C to +120°C, but they are usually dormant at the extremes. Metabolism has been observed for organisms ranging from below -35°C to over 95°C (Ref. 14 and 15). Thus, by inference, it seems reasonable to accept -35°C to +100°C as limits for any active life.

All cells have temperatures at which they perform optimally. These temperatures are cellular and organism specific and span a wide range, from less than 0°C to 70°C. The optimal activity temperatures for the enzymes of a particular cell are approximately the same. However, knowledge of the physical differences between enzymes which have the same function but have different temperature optima is limited. Research along these lines would be useful in understanding life and in evaluating evolutionary theories.

Another important environmental factor is radiation. All organisms are sensitive to radiation but as with other environmental factors, the sensitivity varies greatly from one organism to another. For example, the growth of one species of fungus can be inhibited with a dose of only 0.01 r (roentgens), whereas flies have been irradiated with a dose of 80,000 r but still fly about, eat and behave as usual. Bacteria of the species Pseudomonas have survived 10 million r during eight hours of exposure. The biological damage from radiation is thought to be caused by direct scission or crosslinking of key macromolecules or by the formation of active radicals which in turn react with key macromolecules of the cell. A cohesive general theory of predictive value in radiation studies is not presently available.

I. The Origin of Life on Earth

Life on Earth has apparently evolved in a direct interaction with the terrestrial environment, and it is reasonable to believe that this would hold true for any biological evolution on other planets. Life would have been influenced by and have influenced the physical environment during planetary evolution, and life processes may have been dictated by the starting materials and initial conditions at the time of abiogenesis. Thus, consideration of the origin of life may help elucidate general life principles.

At present, two major theories of the origin of terrestrial life are extant: the panspermia hypothesis and abiogenic chemical evolution. The panspermia hypothesis postulates that life-bearing particles migrate through space. When a planet reaches a requisite stage of habitability, it becomes colonized by these seeds emanating from interplanetary or interstellar space. Spores can survive cryogenic temperatures, vacuum, and radiation. However, the most radiation resistant terrestrial spores would be killed within a day by the intense solar radiation unless they were embedded in a protective medium (Ref. 16). The panspermia hypothesis lacks any supporting evidence. It also shifts attention to transport of organisms and evades the fundamental issue of the origin of life.

In the theory of chemical abiogenesis, life on Earth evolved from spontaneously formed organic matter. It is thus proposed that the known laws of chemistry and physics can lead to the kind of material organization that is recognized as living, given sufficient time, the appropriate resources and a suitable environment (Ref. 17, 18 and 19).

The first step in the development of living from inanimate matter is the formation of relatively large quantities of organic substances on a primitive and lifeless planet. In the past decade, it has been experimentally demonstrated that complex mixtures of organic compounds can be produced by the action of high-energy sources (solar radiation, heat, electric discharge; etc.) on a reducing atmosphere composed of simple gases such as methane, ammonia, hydrogen and water (Ref. 20 to 28). The primitive secondary atmosphere of the Earth is believed to have been of such composition (Ref. 17, 18, 19, 29 and 30) after most of its original hydrogen atmosphere was lost. It is hypothesized that abiogenic synthesis of organic compounds occurred spontaneously after the loss of the primary hydrogen atmosphere.

Since many important biological molecules are polymers, attempts have been made to synthesize polymers abiogenically. Polypeptides (polymers of amino acids) have been formed by thermal polycondensation of amino acids (Ref. 28 and 29) and designated as proteinoids because of their similarity to proteins. Attempts to polymerize nucleotides into the nucleic acids under assumed primeval conditions have met with less success. Although both DNA and RNA polynucleotides have been formed from nucleotide triphosphates in the presence of a polymerase enzyme, such preparations can hardly be called abiogenic.

It is believed that polymer formation took place in the seas protected from the electric and photo-energy in the atmosphere where the monomer units were formed. The moment that living organisms developed, however, the relatively slow spontaneous generation processes must have been cut off simply because living organisms would have rapidly absorbed and utilized the prebiotic molecules available in the premordial hydrosphere. The eventual environmental shift (life-induced) from a reducing to an oxidizing atmosphere may have lowered all abiogenic processes below detectable levels.

The chemical origin and evolution of life is represented schematically in Figure 2. It is hypothesized that environmental conditions allowed the creation of organic molecules and the polymerization of subunits into functional molecules. Eventually, aggregation of molecules took place, providing close association, interaction and protection from the environment. At some stage enclosure occurred. The enclosing surface developed differential permeability to substances transported to and from the environment. The resulting protocells competed for nutrients and slowly evolved into higher, more complex forms capable of reproduction. Those which could best utilize the materials from the environment survived and evolved.

Enclosure of active molecules by some method is necessary for protection against environmental fluctuations, to bring reactants into close association, and to separate an organized inside from a random and disorganizing environment. Only two types of enclosures have been spontaneously formed experimentally. These are the coacervates of Oparin (Ref. 18 and 19) and the thermal proteinoid microspheres of Fox (Ref. 30). Coacervates are obtained from mixtures of solutions of proteins and other high molecular weight substances at different concentrations. Separation occurs leaving sharply demarcated droplets in which the concentration of high molecular weight substances is high, and outside of which it is low. The coacervates do not require complex conditions for formation, are open systems and can selectively concentrate smaller molecules such as dyes, but are relatively unstable.

The microspheres can be formed at room temperature in the presence of the ethyl ester of polyphosphoric acid (Ref. 31). Higher yields can be derived from solutions of proteinoids after brief exposure to hot 1.0% salt solution and subsequent cooling. These self-organized microspheres are much more stable than the coacervates which easily go back into solution. The microspheres retain their form indefinitely, can withstand sectioning for electron microscopy, and can withstand nominal centrifugation. They are also uniform in size, are formed in great abundance, respond to the ionic conditions of the environment, can be forced to undergo septate division by application of pressure and they possess a double layered membrane similar in appearance to that of terrestrial cells. They also incorporate metal ions, have internal streaming, apparently grow and can split ATP (Ref. 28, 29, 30 and 32). The most important differences between Oparin's coacervates and Fox's microspheres are that the former are produced from biologically formed polymers and are somewhat labile, while the latter are composed of proteinoid units derived abiogenically and are highly stable. The importance of these models is that they demonstrate that enclosure and self-organization can occur abiologically. The inference that cellular enclosures actually occurred in a manner similar to either model should not be drawn. The mechanism of membrane formation is not presently understood.

J. Evolution of Life

Evolution occurred initially on two levels--biochemical and cellular. Biochemical evolution was stimulated as heterotrophic* systems, enclosed or not, were rapidly depleting the available abiogenically formed compounds. It became progressively necessary to synthesize the required compounds and those systems which developed this capability possessed a great advantage over others. Thus, as more metabolites were removed from the environment, more efficient biosynthetic capabilities and better methods of protection against being devoured were required for survival. Organisms capable of capturing external energy and transforming it into utilizable form evolved eventually and provided a new source of nutrition to heterotrophic organisms. Photosynthetic and chemolithotrophic organisms are examples of organisms which can capture external energy sources, namely sunlight and inorganic substrate bond energy. These could have, and probably did, evolve later than the heterotrophic forms.

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* Dependent upon preformed organic materials for energy sources.

As life processes became progressively more complex, cellular evolution was required to allow deterministic control of biochemical events in both time and space and to provide mechanisms of defensive value. Only those cells compatible with the evolved biochemistry could develop and progress.

The course of evolution has been influenced by the fact that mortality among competing species is both selective and nonselective. The selectivity arises from differences in competitive efficiency. The nonselective component is due to random environmental events (e.g., catastrophic), which arbitrarily cut back the number of individuals within any given species. In the struggle for survival, the selective Darwinian mechanism is responsible for the progressive elimination of the less fit among the members of a species and for the extinction of those species which cannot compete successfully with others for the available resources. Thus, favorable variations (more efficient) tend to be preserved and unfavorable ones destroyed.

It is presently believed that new forms of life result from structural changes in the DNA, the carrier of the genetic code of inheritance. Such changes are called genetic mutations and can arise at random as a result of : (1) errors during the copying process of the DNA molecule, (2) mechanical or chemical interference caused by ionizing radiation, heat or chemical agents, and (3) possible quantum-mechanical tunneling of hydrogen nuclei affecting the structural characteristics of individual nucleotides (Ref. 33, 34 and 35). The result is a reservoir of variants of varying fitness. These mutations occur spontaneously and are responsible both for the ability of subsequent generations to cope with environmental changes and for species diversification through adaptation to different ecological niches. Most variants are degenerative with only an occasionally advantageous one appearing.

Despite recent advances in systematics, evolution, and genetics, little is presently known about the manner in which higher life forms evolved from lower, simpler forms. The relationship of one species to another is also sometimes obscure. Did metazoa arise independently or evolve from some protozoan phylum? How or why did rickettsia and viruses arise? The answers to these and many other similar questions are simply unknown at present. It may be that some living forms are not interrelated directly by evolution and that their apparent biochemical and other similarities are merely coincidental or the result of ecological interactions or other intrinsic requirements not presently understood.

Besides driving evolution, random changes in the DNA are also thought to be responsible for organism aging and death. It is suggested that the accumulation of such uncorrected errors represents a progressive increase in the noise level of life process systems leading to eventual disruption of activity and loss in functional ability.

III. EXTRATERRESTRIAL LIFE--SOME BASIC HYPOTHESES

A. Apparent Universal Attributes of the Living State

Tentative generalizations of life or life phenomena can only be drawn from available experiences, presently limited to the terrestrial environment. Such generalizations are proposed here and, like other scientific hypotheses, should be regarded neither as absolute or permanent; they are merely intended as an instrument of understanding.

Generalizations of the essential attributes of the living state fall under four categories--namely, hereditary, morphological, metabolic and ecological. These are conclusions drawn from terrestrial life as discussed above and will be used to derive a set of criteria for an extraterrestrial life detection scheme (Section IV of this report).

1. Hereditary

a. An autonomous information system must exist. This system is needed to serve as a memory bank and as a central control agent for life processes. Its capabilities must include storage, readout and transfer of information.

b. The information store must replicate faithfully (fidelity of transfer), the copies being incorporated into derived units. This is essential for species survival and genetic stability from one generation to the next.

c. The information store must be mutable. Survival in the face of environmental change requires capacity for adaptive adjustments.

d. The information store must reside in molecular structure. Information can be stored either in molecular structure or in dynamic processes. Dynamic processes can be interfered with both at high and low temperatures. Molecular structure is affected only at comparatively higher temperatures. Thus, information can be stored more efficiently in molecular structure. Dynamic processes can be stopped by freezing organisms to absolute zero. Terrestrial organisms so treated can recover and function normally (Ref. 36). Thus molecular structure contains the information.

e. Reproduction is necessary for biological continuity. Accumulation of uncorrected molecular errors accompanies continuous biological functioning. Progressive deterioration of the metabolic machinery is inevitable, leading to aging and death. Reproduction accomplished before deterioration has progressed severely assures species survival.

f. The template mechanism is basic to reproduction. Templates offer the simplest and most efficient way to reproduce molecular complexity with fidelity within topological constraints. For example, replication of DNA and formation of biological molecules and organelles are template mediated occurrences.

2. Morphological

a. A basic unit of life is required for reproduction. There are limitations to the degree of complexity which can be faithfully reproduced directly by fission. For example, inhomogeneously organized entities must be precisely formed anew in each generation, since reproduction by splitting is, in this case, impossible. This suggests that a minimum unit of life must exist to initiate growth and development. The minimal size and requirements of terrestrial cells have been investigated (Ref. 2), but cannot be stated categorically.

b. This basic unit cannot grow indefinitely. Size is limited primarily by the amount of turnover materials that must be processed internally for survival as compared to the amount which can cross the boundary per unit time. This suggests that maximum unit size is a function of the volume to surface ratio. If porosity or vacuole formation is used by an organism as a means to increase size at constant volume to surface ratio, then mechanical requirements for structural integrity will still limit size.

c. Enclosure of biological units is necessary. An identifiable boundary must be present to separate an organized dynamic interior from a random disorganized external environment. This will help preserve the state of chemical non-equilibrium that must exist between the two regions. The enclosure must be permeable to turnover materials and impermeable to the genetic and metabolic machinery. This permeability may be passive or active. Enclosure additionally aids in concentrating reactants and therefore aiding chemical reactivity.

d. Diversity is an inherent attribute of life. The course of evolution is influenced by both deterministic (adaptive) and random processes. Although the same ecological niche may be open, different organisms can evolve to fill it at different times and in different situations. Evolution will respond to the detailed ecological requirements. These are time dependent on Earth. Consequently, distinctly different organisms can progressively evolve from a common ancestor. Ecological requirements are expected to be different elsewhere in the universe. Thus, the probability for evolution following the same course twice in separate planetary environments is exceedingly small.

e. The basic structural and morphological features of life species are determined by the molecular constitution of the hereditary material. Functional instructions are resident in the structure of informational macromolecules. Morphogenesis, growth, and development are typical life processes and must be influenced by the information store acting as a control agent. The molecular constitution inside an initial cell determines the growth and development pattern of derived units, either as separate entities or as part of a whole organism.

f. Structure exists throughout biology. Both physical structure and hierarchical structure are important to biology. The physical structure is basic to the function of the conceptually isolated biological entity. The hierarchical structure provides the framework within which the biological entity functions, since no biological entity exists in true isolation.

3. Metabolic

a. Energy must be captured and materials (nutrients) must be extracted from the environment and used metabolically. Energy is at least required to counteract the physical tendency of all systems (including the living) to proceed towards maximum entropy. Energy input is also necessary for maintaining and controlling dynamic processes. Materials are required for physical growth and reproduction.

b. Energy utilization must be accompanied by a release of waste products. It is impossible to convert energy from one form to another at 100% efficiency. Heat and degraded chemical compounds must be produced during any life processes.

c. The rate of energy utilization is influenced by the environment. The stability of any molecular structure decreases with increasing temperature. Consequently, the higher the ambient temperature, the faster a given organism must metabolize in order to evade decay to thermodynamic equilibrium with the environment.

d. Metabolic activities must be under temporal, spatial and quantitative control. Biochemical events preserve survival and, consequently, cannot be random. Their nature and rate must match demands, their sequence must follow an invariant chronological order, and their occurrence must be localized at preselected biological regions. Energy is carefully extracted from the metabolites in gradual steps in which the heat of reaction is too low to disrupt the cell.

e. Metabolic activities necessitate the presence of a chemical solvent. The capability to transport chemical compounds is essential for biological functioning. A chemical solvent is, therefore, required to carry reagents, information and products of reaction in solution or suspension.

f. Macromolecules are basic to life chemistry. Large molecular size provides stability in the event of environmental change and preserves function specificity. Macromolecules stand out in terrestrial biology. The structure of the small but highly specific enzyme active site is critical. Large molecular structure enables the rigid maintenance of active sites despite the effect of random thermal motion. Although small molecules can also be rigidly configured, the enzyme (catalyst) must firmly hold the substrate or substrates (and often a cofactor as well) in a rigid specific relationship. Since the molecules are usually large (simple monomer sugar units are over 150 amu in mass), the enzyme must be large with respect to the molecules on which it works to prevent local deformation during the reaction.

g. Metabolic macromolecules and informational macromolecules must be physically distinguishable. A code is therefore necessary to translate the stored information. Metabolism is a dynamic process during which reacting molecules are alternately constructed, degraded and their components reused. Reutilization of molecular units promotes maximum efficiency in a molecular chemistry. Since informational macromolecules must remember and control biochemical events, they must also remain unaffected by them. It follows that transfer of information is necessary. This is possible only if both a code and a chemical intermediary exist.

h. The functional specificity of metabolic macromolecules is determined by their molecular structure. The transfer of instructions from the hereditary material to the metabolic machinery must be mediated through molecular structure. Structural specificity among all interacting macromolecules is necessary to interpret and execute all instructions and to maintain a controlled dynamic biochemistry.

i. Life chemistry is molecular and not atomic. Molecules are necessary to provide the complex structural specificity required for biological functioning.

j. Biological molecules must be sterically consistent. The functional specificity of metabolic macromolecules is determined by their three-dimensional structure. Consequently, a discrimination among optical isomers of available compounds will naturally occur during biogenic synthesis of highly defined nonrandom macromolecules.

4. Ecological

a. The availability of radiant (stellar) energy is basic to the existence of life. Environments in a state of thermodynamic equilibrium cannot provide the energy required to drive biological activity. Available indigenous energy sources are subject to eventual depletion in geological time. Consequently, photosynthetic mechanisms are required to sustain planetary ecologies indefinitely, although other sources can be used for geologically short periods.

b. High temperature imposes at least one definite limit to life processes. The structural and, therefore, the functional specificity of biological macromolecules is first interfered with and then destroyed as ambient temperature rises. Breakdown of the metabolic machinery (including its control) followed by death is inevitable at high enough temperatures. On the other hand, there is no inherent reason why life cannot survive temperatures approximating absolute zero.

c. The existence of only one species within an isolated habitat must be precluded. Evolutionary processes argue against the development and propagation of only one species. Additionally, a single species cannot close the ecology and is heading for extinction as a result of eventual depletion of nutrients and overaccumulation of waste products.

d. The course of evolution is influenced by the environment and vice versa. Compatibility of life and environment is essential for survival. Species interacting most favorably with the existing ecology will be preserved; unfavorable ones will be eliminated by competition. Evolution is the result of a long series of adaptations and competitive eliminations.

e. Control is necessary on all levels of biological organization. One of the most obvious characteristics of biological organisms is that processes must be ordered in time. This is seen in circadian rhythms, cellular regulation, as well as in digestion and food gathering. Other examples of control action include predator-prey relationships, population self-regulation, and nutrient cycling (e.g., nitrogen). Control systems utilizing various feedback mechanisms have been discovered in all levels of biological organization.

Simple organisms are required in any ecology. Microorganisms by virtue of their size, functional diversity, genetic variability and high growth and reproductive rates, respond quickly to environmental change. These properties also enable them to close the cycling of ecological materials and to help ensure survival during periods of change. They also are highly efficient for continually probing the environment for new niches in which to expand the biomass. Finally, they constitute the foundation out of which complex organisms may evolve.

g. Microbiota can sustain a closed biochemical ecology. Simple organisms do not necessarily have to depend on higher forms for survival. They preceded in time the evolution of higher forms of life, and had to form a closed ecology. All terrestrial ecologies include microbiota.

h. The coexistence of different species within a closed ecology requires that they share basic biochemical characteristics. In a closed ecology, members of one species must be able to absorb and incorporate into themselves either the material make-up of other species or their waste products, since no ecology can be composed of only primary energy converters. This suggests that the basic building blocks of life within a closed ecology must be either chemically similar and spatially consistent (homologous optical isomers) or interchangeable into compatible forms.

i. The biochemical pathways will probably be unique to life on a given planet. Complex chemical reactions involving a variety of intermediates are required to sustain life. The evolved bio-synthetic schemes and energy transforming processes result from long-term interaction with the environment, and are probably unique to a planetary ecology.

j. If life exists on a planet, it is also widespread over its surface. The tendency of the biomass to fill all available ecological niches of the available environment through evolutionary adaptation coupled with surface circulation phenomena, will tend to spread life over the entire planet, if survival there is at all possible. Environmental variations, however, should be expected to affect the variety, density and distribution of the existing species on both a global and micro scale.

k. Abiogenic life precursors compounds may be universal. Abiogenic products seem to be highly independent of the energy source used to generate them, and greatly independent of the composition of the environment providing it is reducing in nature or contains reducing contaminants. Abiogenesis of organic compounds does not seem to occur in purely oxidizing environments. Thus, the initial starting materials of life may have been the same everywhere (e.g., Earth, Mars, Venus and the Moon).

B. Life Chemistries

Terrestrial biochemistry is apparently well suited to the needs of life. It is natural, however, to ask whether or not alternate biochemistries can exist where conditions bar the existence of conventional (terrestrial) life.

The possibility of life based on multivalent elements other than carbon (e.g., silicon) and solvent other than water (e.g., ammonia) has been suggested and debated since the beginning of the century (Ref. 14, 37, and 38). Supporters of the theory that exotic life could exist argue that fundamental biological processes are not understood well enough to preclude any such life. Their opponents argue that enough is already known about non-carbon chemistries to preclude any such life.

They further argue that universality in biochemical selectivity is perhaps demonstrated by the fact that terrestrial life is carbon based despite the overwhelming abundance of silicon relative to carbon on this planet. However, elemental abundances at the Earth's surface could have been different at the time of biogeny. The relative elemental constitution of cellular protoplasm is compared to cosmic and terrestrial abundances in Table III.

Since biochemical uniqueness is a subject in itself, it is the content of a companion report (Ref. 38). This report concludes that hydrogen, carbon, nitrogen and oxygen are the necessary constituent atoms in biological molecules. Under unusual conditions ammonia might be a suitable replacement for water.

IV. APPROACH TO THE BIOLOGICAL EXPLORATION OF THE PLANETS

A. Selection of Scientific Strategy

The search for extraterrestrial life (past or present) has been recommended as an undertaking of great significance because of its scientific importance, its philosophical implications and its emotional appeal (Ref. 41).

Detecting life on other planets of the solar system by direct observation from Earth is not possible. The alternative is to design and build appropriate scientific equipment that can be flown in space vehicles and can perform definitive experiments on the surface of, or in orbit about, any given planet.

In order to accomplish this objective, operational limitations of the approach must be identified, and operational assumptions about alien life must be made in order to establish a framework upon which the broad aspects of the search are based. In addition, criteria based upon assumed generalizations of life must be established so that decisions can be made on the necessary measurements.

B. Operational Limitations

Detection of life in unfamiliar environments is a complex task. Candidate schemes involving planetary probes are limited by the following constraints:

1. In-situ automated preprogrammed experiments involve complicated sampling and sample handling methods.

2. Representative surface, subsurface and atmospheric samples must be acquired to yield meaningful inferences about the environment.

3. The equipment must not contaminate the sample with viable or non-viable organic material from Earth at any time.

4. The sample must be prepared for analysis and be analyzed by processes which are applicable to the indigenous life (one must approximately know what he is looking for).

5. Detection of life must not rely on a single explicit test, since there is none. Complimentary experiments are necessary to avoid ambiguity.

6. Adequate data handling and telemetry equipment must be included to assure reliable communication to the investigators.

C. Operational Assumptions

On the basis of the postulated generalizations (Section IIIA), the following working assumptions are suggested in order to allow the definition of appropriate search criteria within the above stated limitations.

1. Alien life, if present, is based on carbon-water chemistry similar but not necessarily identical to that of terrestrial life. Non-carbon chemical systems appear to be improbable (1d, 3e, 4k).*

2. If life exists on a planet, it should be manifested by some kind of metabolic attributes (1e, 3a, 3b, 3c, 3d).

3. Detection and biochemical characterization of a single extraterrestrial life unit are tantamount to the determination of the basic biochemical characteristics for all life on the target planet (4h, 4i).

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* Numbers in parentheses refer to pertinent generalizations from Section IIIA. The references are of varying degree of inference.

4. If life has evolved on a planet, it is probably sufficiently widespread to be encountered at any given site selected at random. Nevertheless, careful selection of specific target areas, most compatible to life, is desirable in order to increase the probability of its detection (4c, 4d, 4g, 4j).

5. Radiant energy is necessary to drive any planetary ecology. All other energy sources are less permanent and, therefore, appear less likely (3a, 4a).

6. The detection of a single extraterrestrial life unit confirms the existence of a closed planetary ecology consisting of a variety of coexisting species (4c, 4h).

7. The characteristic morphology of possible life on another planet most likely will differ from that of terrestrial life (2d, 4d).

8. The search for extraterrestrial life can take the form of a microbiological experiment, inasmuch as simple organisms can sustain a closed ecology and can exist with or without higher forms of life. This is important because miniaturized equipment can be used, allowing small sample acquisition which contains a great number and variety of intact and therefore minimally disturbed life forms (2a, 2b, 2c, 4f, 4g).

9. Terrestrial organisms can adapt to and spread in extraterrestrial environments. Spacecraft sterilization to some extent is required in order to prevent biological contamination of the planets before they can be characterized and the basic questions answered (1c, 2d, 4j).

10. Extraterrestrial life can adapt to terrestrial conditions. It may also possess or eventually acquire properties pathogenic to terrestrial organisms. Consequently, any form of alien life should be regarded as potentially dangerous and safeguards must be taken before its introduction into the terrestrial biosphere (1c, 4f).

D. Criteria Barring the Existence of Life*

1. High planetary temperatures. Sufficiently high temperatures interfere with controlled reactions and favor chemical degradation (1d, 2f, 3d, 3h, 4b, 4e).

2. Extremely low planetary temperatures permanently present. Molecular reactions would occur too slowly to allow biochemical evolution (3c).

3. The absence of an atmosphere and of a liquid medium past and/or present. Abiogenesis can occur only where molecular transport and mixing is favored (3e, 4d).

4. Signs of environmental evolution being due to strictly geophysical processes. For example, a planetary atmosphere in a state of chemical equilibrium. Biological activity affects the environment and is responsible for non-equilibrium conditions (3b, 4d).

5. The absence of a sufficiently high radiant energy flux (3a, 4a).

6. The absence of carbon-based macromolecules (1d, 2f, 3f, 3h, 3i, 4k).

7. The absence of observable organized structures at macroscopic and microscopic levels (2a, 2b, 2c, 2f).

8. The absence of net optical rotation in extracts of any of a large number of samples. Optical isomers generally occur in equal amounts except when formed biologically. The ratio of D to L residues in terrestrial glucose is about 10^{15} to 1 (3j).

9. The absence of any signs of life in any of a large number of samples taken randomly over the target planet (2d, 4f, 4j).

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* The criteria are not ranked in order of importance. While it is not necessary to satisfy all of the individual statements for a target planet, in general the more that are satisfied, the stronger the inferences drawn.

E. Criteria Suggesting the Possible Existence of Life

1. Availability of water (3e, 4d).

2. A local temperature range permitting water to exist in liquid form at least periodically (3c, 3d, 3e, 3h, 4b, 4e).

3. Abundance of radiant flux (3a, 4a).

4. Seasonal surface activity (3a, 4j).

5. A planetary atmosphere in a sustained state of chemical non-equilibrium (3b, 4d).

6. Characteristic electromagnetic emission or absorption spectra suggestive of life-associated molecules (3a, 3b).

7. Presence of complex organic molecules. Macromolecules seem to be present naturally only where life is or was present. Infall of carbonaceous chondrites will result in deposition of hydrocarbons. Also note that typical abiogenic organic compounds (possibly life precursors) are inevitably produced in reducing environments (1d, 2f, 3f, 3i, 4k).

8. Net optical rotation in extracts of suspect samples (3j).

9. Characteristically organized structures suggestive of living organisms on various size scales, fossils or artificial creations (2a, 2b, 2c, 2d, 2f, 3h, 4f).

10. Active chemistries suggestive of metabolism in samples obtained from the atmosphere, surface or subsurface of planet (1e, 3a, 3b, 3d, 3e).

11. Geological features not attributable to purely physical or chemical processes (3b, 4d).

12. Non-random movement of suspect organized units (3a, 4e).

F. Criteria Confirming the Existence of Life

1. Purposeful response of organized structures to physical and perceptual stimuli (3a, 4e).

2. Unmistakably biological morphologies (including fossils) or artificial structures (2a, 2c, 2f, 4f).

3. Unmistakably biological activities such as metabolism, growth, reproduction and death as an end point (1e, 3a, 3b, 3d, 4i).

4. Self-directing, self-propagating increase in local ordering (decrease in local entropy) that cannot be explained by non-biological mechanisms (2c, 3a).

5. A combination of several of the criteria given in Section E. The number necessary for this and the restriction that they be demonstrated on any one sample define the rigor with which the existence of life can be confirmed (appropriate combination of references).

G. Program Planning

A simple direct program for the detection of extraterrestrial life is desirable but difficult because:

1. The necessary technological capability (automated instruments and methods) has not been developed for a search paralleling the scope with which it could be done in a terrestrial lab.

2. One is not quite sure what he is looking for.

3. Even if the necessary equipment were available, a comprehensive program would be too expensive.

4. Each probe or experiment package carries the risk of contaminating the target planet with terrestrial microbes which could complicate the interpretation of results (Ref. 42, 43, 44).

Thus, instrument availability, experiment definition, program cost, and contamination risk are the factors constraining the scope and nature of a life detection program. Scientists must add the other dimension and decide what they will accept as confirmation of life, and what inferences they are willing to make on the basis of returned data. The criteria in this paper represent one attempt to help in the scientist's role.

A systematic overall program development sequence for the biological exploration of the solar system is depicted in Figure 3. Pertinent scientific activities and available mission modes to carry out these activities are identified in the Figure. The first logical step is to obtain information about the physical characteristics of the planets inasmuch as life depends on and evolves with the environment. Such information will be valuable for the selection of promising planetary targets, for discriminating among candidate landing sites and for insuring successful descent and deployment of planetary probes.

It appears wise to include the broad scientific survey of the solar system early in the program. This could help in establishing target options and priorities and could also yield some unexpected information significant enough to warrant a change in perspectives.

The next important step would be to place a highly instrumented package on the surface of the target planet and conduct a battery of appropriate biological experiments. Three major classes of experimentation are available: (1) visual imagery, (2) chemical identification of molecular complexes of possible biological relevance, and (3) observation of characteristic life processes. Such a program would involve the use of specific apparatus designed to investigate some particular property (e.g., chemical, metabolic, etc.) of possible extraterrestrial life. Experiments based on these instruments have been reviewed by several authors (Ref. 45 and 46), and some of the hardware has been built and tested successfully in severe terrestrial environments. Table IV shows some of these instruments together with their scientific capabilities and systems requirements. The concept of an unmanned automated biological laboratory capable of performing and integrating a multiplicity of experiments has also received detailed consideration (Ref. 53).

The study of extraterrestrial life could be carried out in greatest detail in terrestrial laboratories on returned planetary samples since the intellectual and methodological resources that could then be applied are virtually limitless

(Ref. 54). This possibility has already received attention; both unmanned and manned (Refs. 55 and 56) schemes have been proposed. In principle, planetary sample return could constitute the ultimate step if information received from unmanned landers indicates favorable prospects. This suggests that phase 3 in Figure 3 should preferably follow the completion of phase 2.

In order to protect the terrestrial biosphere from incoming alien contamination, a quarantine facility should be available outside the terrestrial environment. Sterilization, in Earth orbit, of unmanned probes returning from the planets, does not preclude the possibility of back-contamination, since foreign particles adhering to the probes might be dislodged during orbital capture operations and drift to Earth. A moon base established primarily for other functions could be used as an interim facility for biological containment and quarantine. Sterile recovery, storage, and return of planetary samples must be assured on manned missions. Otherwise, the manned flights must be preceded by "in-situ" unmanned experiments designed to resolve the question of back contamination hazard.

Retrieved planetary samples must be preserved in an uncontaminated condition during the return trip to Earth to assure meaningful subsequent analysis. Consequently, research is necessary to establish methods for preservation and/or encapsulation of samples. In case of manned planetary missions, preliminary analyses of the samples can be made by a biologist-astronaut immediately after sample acquisition.

A general approach for mission planning is depicted in Figure 4. The established biological criteria are used together with accepted planetary environment models to identify promising targets. Appropriate biological experiments are then determined on the basis of: (a) description of life amenable to experimental observation, (b) our knowledge of planetary environment, and (c) the selected mission mode. After mission completion, the returned data is analyzed and interpreted. Based on both this interpretation and the established criteria, biological inferences are drawn and used: (a) to update the initial hypotheses concerning life (if warranted), and (b) to define the next generation effort. Non-biological inferences are also drawn and used to update the physical model of the target planet.

H. Consequences of the Biological Exploration of the Planets

The search for extraterrestrial life introduces a new dimension of inquiry into biology. Any information will be of great interest.

The unparalleled opportunity to detect extraterrestrial life may be irrevocably lost if terrestrial microorganisms carried by deep space probes contaminate the planets. Some degree of sterilization of deep space probes which are intended to descend or might accidentally impact the planets is, therefore, required for any responsible planetary effort.

Ultimately, controlled contamination of a sterile planet with terrestrial microorganisms could be used as a means for promoting geochemical, atmospheric and even climatic changes in a directed way. Exploitation of the planets in the distant future could thus become possible.

The introduction of alien forms of life into the terrestrial biosphere by spacecraft returning from the planets is a potential hazard that must be considered early. Safeguards must be defined and implemented as carefully as possible.

An intelligent exobiology program has the promise of returning results of great significance regardless of whether or not life is discovered. For instance:

1. Failure to detect life would provide an index of the requirements for life.

2. Detection of chemical precursors of biological organizations would yield information on the course of biochemical evolution and its generality as well as on the origin of life itself.

3. Detection of extraterrestrial life fundamentally similar to that on Earth would suggest a universal biochemical uniqueness.

4. Detection of extraterrestrial life fundamentally different from that on Earth would provide an answer to the question of exotic biochemistries and would suggest that life may be a common occurrence in the universe.

Great care must be taken in implementing any planetary space programs, because only a few targets which can honestly be hoped to provide promising biological information are available in our solar system. At present, it seems improbable that such investigations can be carried out elsewhere in the universe. It is believed that a carefully planned, coordinated and implemented search for extraterrestrial life will supply answers of great biological and philosophical significance.

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D. B. Hoffman

A. N. Kontaratos

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Attachments
Tables I-IV
Figures 1-4

REFERENCES

1. Horowitz, N. H. "The Biological Significance of the Search for Extraterrestrial Life." Advances in Astronomical Sciences, Vol. 22, 1967.

2. Morowitz, H. J. "Biological Self Replicating Systems." In Snell, F., Ed. "Progress in Theoretical Biology," Vol. I. New York, Academic Press, 1967.

3. Morowitz, H. J. "Energy Flow in Biology." New York, Academic Press, 1968.

4. Grodins, F. S. "Control Theory and Biological Systems." New York, Columbia University Press, 1963.

5. Reiner, J. M. "The Organism as an Adaptive Control System." Englewood Cliffs, N. J., Prentice-Hall, 1968.

6. Kalmus, H. "Regulation and Control in Living Systems." New York, John Wiley and Sons, 1966.

7. Milsum, J. H. "Biological Control Systems Analysis." New York, McGraw-Hill, 1966.

8. "Significant Achievements in Space Bioscience 1958-1964." Washington, D. C., NASA SP-92, 1966.

9. "Life in Extraterrestrial Environments." IIT Research Institute Report No. IITRI-26023-5, 1966.

10. "Life in Extraterrestrial Environments." IIT Research Institute Report No. IITRI-26023-9, 1967.

11. "Life in Extraterrestrial Environments." IIT Research Institute Report No. IITRI-26023-10, 1967.

12. Siegel, S. M., G. Renwick, O. Daly, C. Giumarro, G. Davis, and L. Halpern. "The Survival Capabilities and the Performance of Earth Organisms in Simulated Extraterrestrial Environments." In Mamikunian, G., and M. H. Briggs, Eds. "Current Aspects of Exobiology." 119-178. New York, Pergamon, 1965.

13. Young, R. S. "Extraterrestrial Biology." New York, Holt, Rinehart and Winston, Inc., 1966.

14. Firsoff, V. A. "Life Beyond the Earth." New York, Basic Books, 1963.

15. Brock, T. D. "Life at High Temperatures." Science 158: 1012, 1967.

16. Shklovskii, I. S., and C. Sagan. "Intelligent Life in the Universe." San Francisco, Holden-Day, Inc., 1966.

17. Oparin, A. I. "The Origin of Life." New York, Dover, 1953.

18. Oparin, A. I. "Life: Its Nature, Origin and Development." New York, Academic Press, Inc., 1964.

19. Oparin, A. I. "The Chemical Origin of Life." Springfield, Ill., Thomas, 1964.

20. Miller, S. L., and H. C. Urey. "Organic Compound Synthesis on the Primitive Earth." Science 130: 245, 1959.

21. Miller, S. L., and N. H. Horowitz. "The Origin of Life." In Pittendrigh, C. S., W. Vishniac, and J. P. T. Pearman, Eds. "Biology and the Exploration of Mars." Washington, D. C., Nat. Acad. Sci. Publication 1296, 41-69, 1966.

22. Miller, S. L. "The Formation of Organic Compounds on the Primitive Earth." Annals of the New York Acad. of Sciences 69: 26, 1957.

23. Oro, J., and A. P. Kimball. "Synthesis of Purines Under Possible Primitive Earth Conditions I. Adenine from Hydrogen Cyanide." Arch. of Bioch. and Bioph. 94: 217, 1961.

24. Oro, J., and A. P. Kimball. "Synthesis of Purines Under Possible Primitive Earth Conditions II. Purine Intermediates from Hydrogen Cyanide." Arch. of Bioch. and Bioph. 96: 293, 1962.

25. Oro, J. "Studies in Experimental Organic Cosmochemistry." New York Acad. of Sci., 108: 464, 1963.

26. Ponnamperuma, C., R. M. Lemmon, R. Mariner, and M. Calvin. "Formation of Adenine by Electron Irradiation of Methane, Ammonia, and Water." Proc. Nat. Acad. Sci., 49: 373, 1963.

27. Ponnamperuma, C., and P. Kirk. "Synthesis of Deoxyadenosine Under Simulated Primitive Earth Conditions." Nature, 203: 400, 1964.

28. Fox, S. W. "How Did Life Begin?" Science 132: 200, 1960.

29. Fox, S. W. "The Terrestrial Origins of Macromolecules and of Cells." Information Exchange Group No. 7. Washington, D. C., Government Printing Office, 1965.

30. Fox, S. W., and T. Fukushima. "Electron Micrography of Microspheres from Thermal Proteinoid." In Deborin, G. A., et al., Eds. "Problems of Evolutionary and Industrial Biochemistry." Moscow, U.S.S.R. Publishing House, 1964.

31. Young, R. S. "Microspheres from Proteinoid." In Fox, S. S., Ed. "The Origins of Prebiological Systems." New York, Academic Press, 1965.

32. Fox, S. W. "Experiments With a Precellular Model." In Jacobs, G. J., Ed. "Proceedings on a Conference in Theoretical Biology." NASA SP-104, 121-138, 1966.

33. Schrodinger, E. "What Is Life." Doubleday, 1956.

34. Lowdin, P. O. "Quantum Genetics." International Science and Technology, May, 1963.

35. Lowdin, P. O. "Proton Tunneling in DNA and Its Biological Implications." Reviews of Modern Physics, Vol. 35, No. 3., July, 1963.

36. Skoultchi, A. I., and H. J. Morowitz. "Yale Journal Biol. Med." 37: 158, 1964.

37. Wald, G. "Life in the Second and Third Periods; or Why Phosphorus and Sulfur for High Energy Bonds?" In Pittendrigh, C. S., Ed. "Extraterrestrial Life: An Anthology and Bibliography." Washington, D. C., Nat. Acad. Sci. Publication 1296A, 285-300, 1966.

38. Schulman, S. G. "On the Possibility of Exotic Biochemistries." TR-68-710-9, December 17, 1968.

39. Edsall, J. T., and J. Wyman. "Biophysical Chemistry." Vol. 1. New York, Academic Press, 1958.

40. Mason, B. "Principles of Geochemistry." Third Edition. New York, John Wiley and Sons, 1966.

41. "Biology and the Exploration of Mars--Conclusions and Recommendations." Nat. Acad. of Sciences Publication 1296, National Research Council, 1966.

42. Horowitz, N. H., R. P. Shays, and R. W. Davies. "Planetary Contamination I: The Problem and the Agreements." Science 155: 1501, 1967.

43. Murray, B. C., M. E. Davies, and P. K. Eckman. "Planetary Contamination II: Soviet and U. S. Practices and Policies." Science 155: 1505, 1967.

44. Sagan, C., E. C. Levinthal, and J. Lederberg. "Contamination of Mars." Science 159: 1191, 1968.

45. Quinby, F. H., Ed. "Concepts for Detection of Extraterrestrial Life." Washington, D. C., NASA SP-56, 1964.

46. Hanrahan, J. S., Ed. "The Search for Extraterrestrial Life." Sun Valley, Calif., Scholarly Publications, Inc., 1967.

47. Fernandez-Moran, H. "Analytical Systems for Biological Study of Mars." NASA CR-75702, 1965.

48. "Biological Specimen Storage for Extended Space Missions." Spacelabs, Inc., Contract NASW-1556, 1967.

49. Brigden, W. H., and J. Roman. "New Miniaturized Gas Analyzer." Aerospace Medicine 37: 1037, 1966.

50. Lem, J. D., Jr. "Application of Gas Chromatography in Manned Space Flight." Aerospace Medicine 38: 1110, 1967.

51. Bentley, K. E., et al. "Detection of Life-Related Compounds on Planetary Surfaces by Gas Chromatography-Mass Spectrometry Techniques." Jet Propulsion Laboratory Technical Report 32-713, August 30, 1965.

52. "Detection of Extraterrestrial Microorganisms by Microcalorimetry." NASA Contract No. NAS2-3477, 1966.

53. "Study of the Automated Biological Laboratory." Aeronutronic Division of Philco-Ford Corp., Contract NASw-1065, 1965.

54. Horowitz, N. H. "The Impact of Manned Spaceflight on the Exobiology Program." In "Biology and the Exploration of Mars." Nat. Acad. of Sciences Publication 1296, National Research Council, 1966.

55. Thompson, W. B., et al. "Experiment Payloads for a Manned Mars Flyby Mission." Bellcomm TR-67-233-1, May 15, 1967.

56. Thompson, W. B., et al. "Experiment Payloads for Manned Encounter Missions to Mars and Venus." Bellcomm TR-68-710-2, February 21, 1968.

TABLE I

CHARACTERISTICS OF TERRESTRIAL LIFE

PRIMARY	SECONDARY	TERTIARY
Hereditary	Memory Control Mutability	Genetic Continuity Morphogenesis Specialization Adaptation Evolution
Morphological	Structure Function Organization	Molecules Organelles Cells Tissues Organs Organisms
Metabolic	Energy Capture Energy Transformation* Materials Exchange*	Homeostasis Respiration Growth Self-Repair Reproduction Death
Ecological (Interactions among populations and environment)	Energy Flow Materials Cycles Succession Stability	Biochemical Compatability Trophic Pyramid Competition Predation Mutualism Parasitism Evolution

* Include waste production.

TABLE II*

ENVIRONMENTAL EXTREMES AT WHICH ORGANISMS CAN FUNCTION**

PHYSICAL FACTOR	LOWER LIMIT	UPPER LIMIT
Temperature	-35°C	104°C
Pressure	10^{-9}mmHg	1400 atm
pH	0	13
Salinity	Double distilled water	Saturated brines (25% salt)
Eh (Redox potential)	-450 mv at pH 9.5	+850 mv at pH 3
O_2	0%	100% at 1 atm.

ENVIRONMENTAL EXTREMES AT WHICH ORGANISMS CAN SURVIVE

PHYSICAL FACTOR	LOWER LIMIT	ORGANISM	HIGHER LIMIT	ORGANISM
Temperature	-273°C	Bacterial Spores (many species)	188°C	Bacillus subtilis niger (exposure time 1 minute)
Radiation	Essentially 0	----	10^7 rad	Pseudomonas

* Lower and upper limits do not necessarily refer to the same organism.

** Data from many sources but especially from Ref. 8.

TABLE III

ATOM PERCENT ELEMENTAL COMPOSITION COMPARISONS (REF. 3, 39, 40)

	Universe(40)	Sun(40)	Sea Water(39)	Earth's Crust(39)	Man(3)	Alfalfa(3)	Copepod(3)	Bacteria(3)
Carbon		0.0448	0.0008		19.37	11.34	6.1	12.14
Hydrogen	92.7	86.36	66.42		9.31	8.72	10.21	9.94
Nitrogen	0.0354	0.0081			5.14	0.825	1.52	3.04
Oxygen	0.0498	0.0782	33.21	62.55	62.81	77.9	79.99	73.68
Phosphorus					0.63	0.71	0.13	0.6
Sulfur	0.0009	0.0016	0.0946		0.64	0.1	0.14	0.32
Calcium	0.0001	0.0001	0.0034	1.94	1.38	0.58	0.04	0.03
Sodium	0.0004	0.0002	0.158	2.64	0.26	0.03	0.54	0.06
Potassium	0.0001		0.0033	1.42	0.22	0.17	0.29	0.05
Magnesium	0.0021	0.0019	0.018	1.84	0.04	0.08	0.03	0.03
Chlorine			0.0176		0.18	0.07	1.05	
Iron	0.0014	0.0003		1.92	0.005	0.0027	0.007	
Silicon	0.0023	0.027	0.0001	21.22	0.004	0.0093	0.007	
Zinc					0.0025	0.0004		
Copper					0.0004	0.0003		
Aluminum	0.0002	0.0001		6.47	0.0001	0.0025		
Helium	7.19	13.47						
Nickel	0.0006	0.0001						

TABLE IV

SOME SUGGESTED INSTRUMENTATION FOR EXTRATERRESTRIAL LIFE DETECTION

INSTRUMENT	WEIGHT	VOLUME	POWER REQ.	RESOLUTION	AVG. LIFETIME	COMMENTS	REF.
Fixed focus electron microscope	50 lbs			100Å			General
Culture growth experiment with spectrophotometer	50 lbs						General
Mass spect. gas chromat.	50 lbs						47
Pressure Sensor	1						47
Temp. Sensor	1						47
Freezer	15-22 lbs.	300-500 in^3					48
Gas Analyzer	28 lbs	1000 in^3	≤50 watts		250 hrs	Operation at ±6°C about ambient.	49
Gas chromatograph	12 lbs	850 in^3	8-10 watts	10 ppm		80 minutes	50
Gas chromatograph	100 gr.						51

TABLE IV (Continued)

INSTRUMENT	WEIGHT	VOLUME	POWER REQ.	RESOLUTION	AVG. LIFETIME	COMMENTS	REF.
Mass spectrometer	2.7 kg		5 watts	mass 30			51
Gas chromatograph Mass spectrometer	7 kgm		10 watts		sev. days		51
Fixed focus electron microscope	1 ft long			100Å		continuous scan	47
Vidicon microscope		7" long		0.5μ		Fixed focus 100μ field	45
Gas chromat. Mass spect.	5-14 lbs					10 sec. analysis cycle	45
Radio isotope biochem probe (Gulliver)	3 oz	25° in^3					45
Microcalorimeter	31 lbs	6700 in^3	<10 watt hrs/cycle			Detect 2.8×10^9 E.coli bact in resting state or 1.5×10^6 in most active state	52
Metabolic life detection subsystem	18±3 lbs	1210 in^3	30 watt min				46

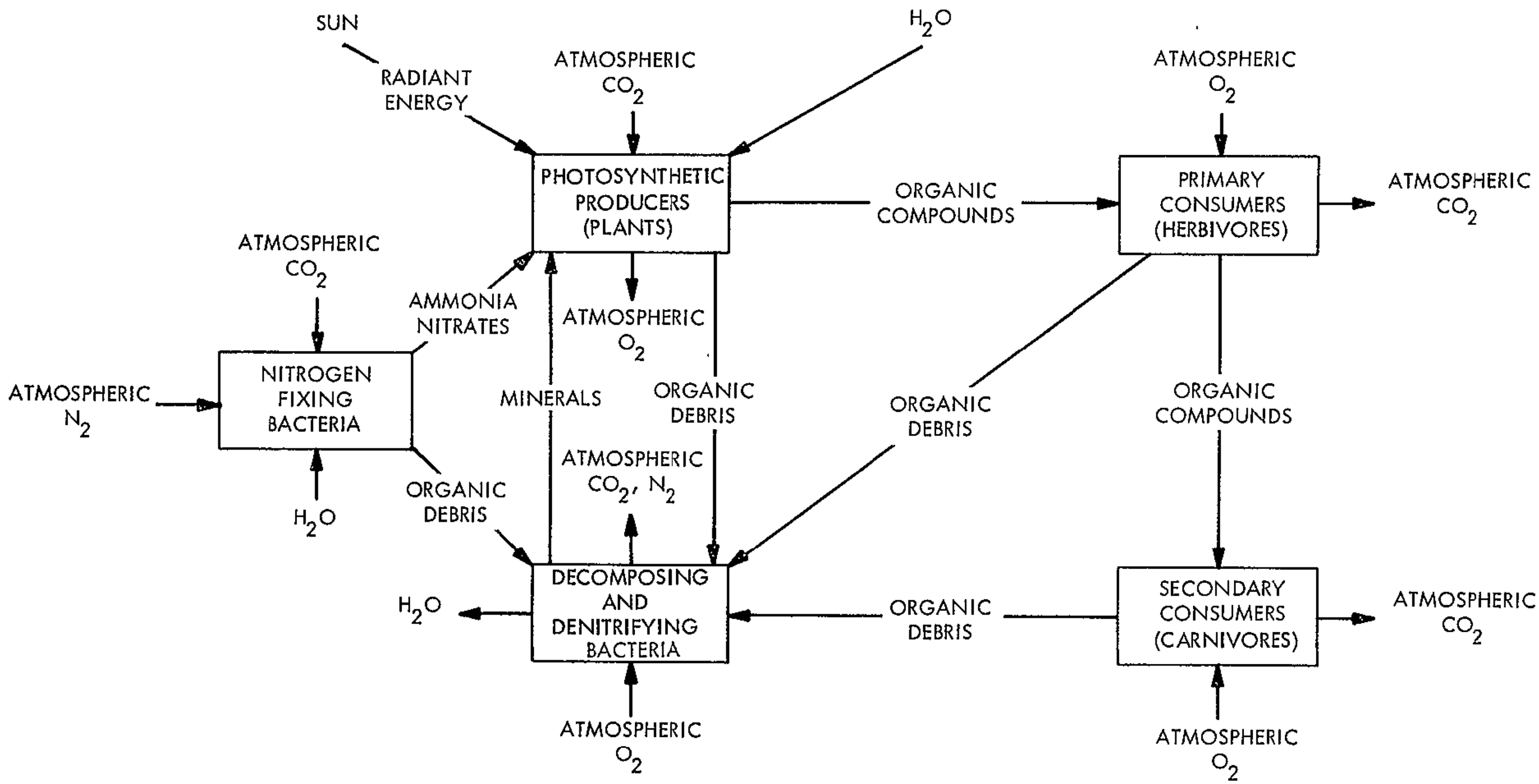

FIGURE 1 — ENERGY UTILIZATION AND THE CYCLE OF MATTER

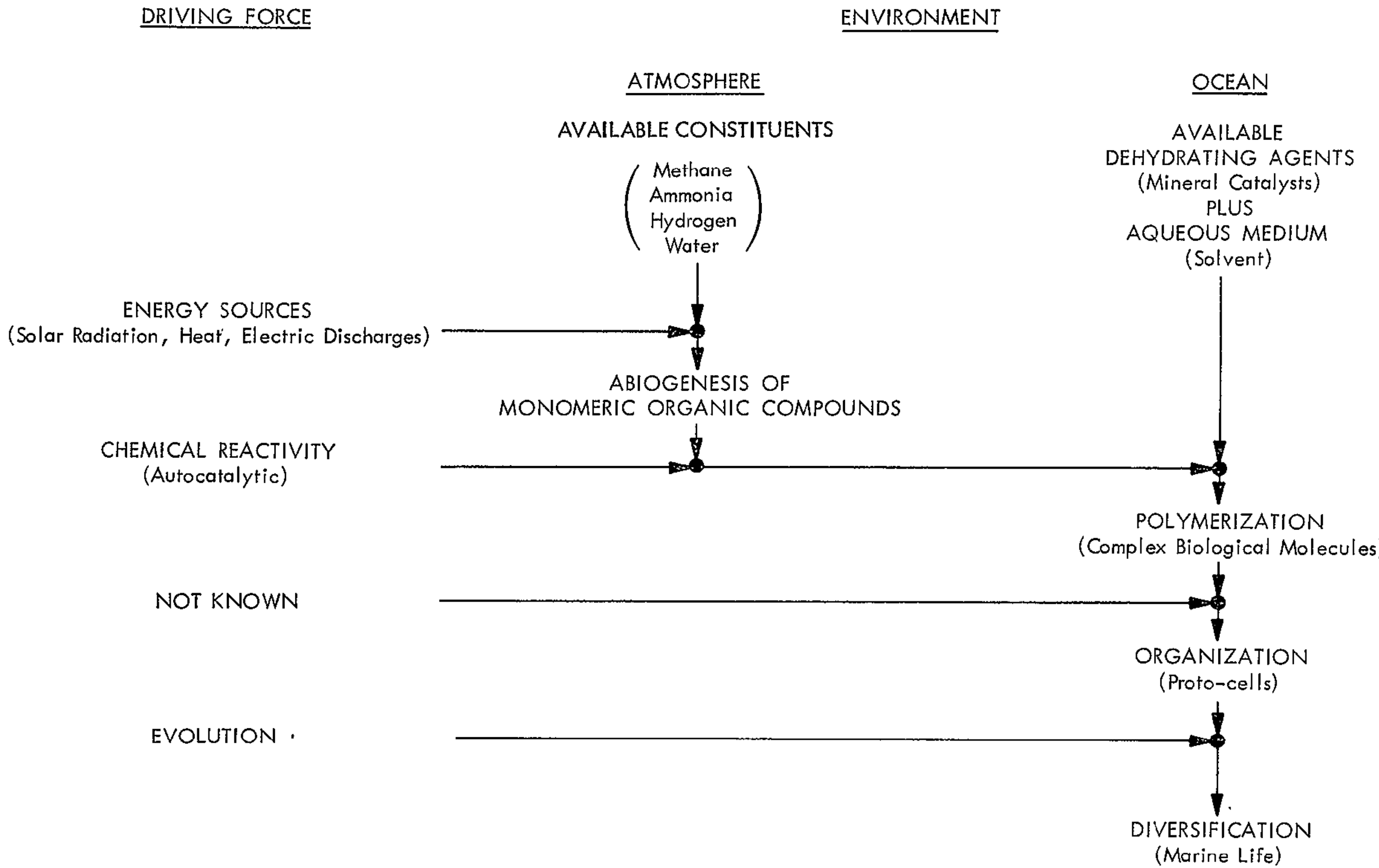

FIGURE 2 — CHEMICAL ORIGIN OF LIFE

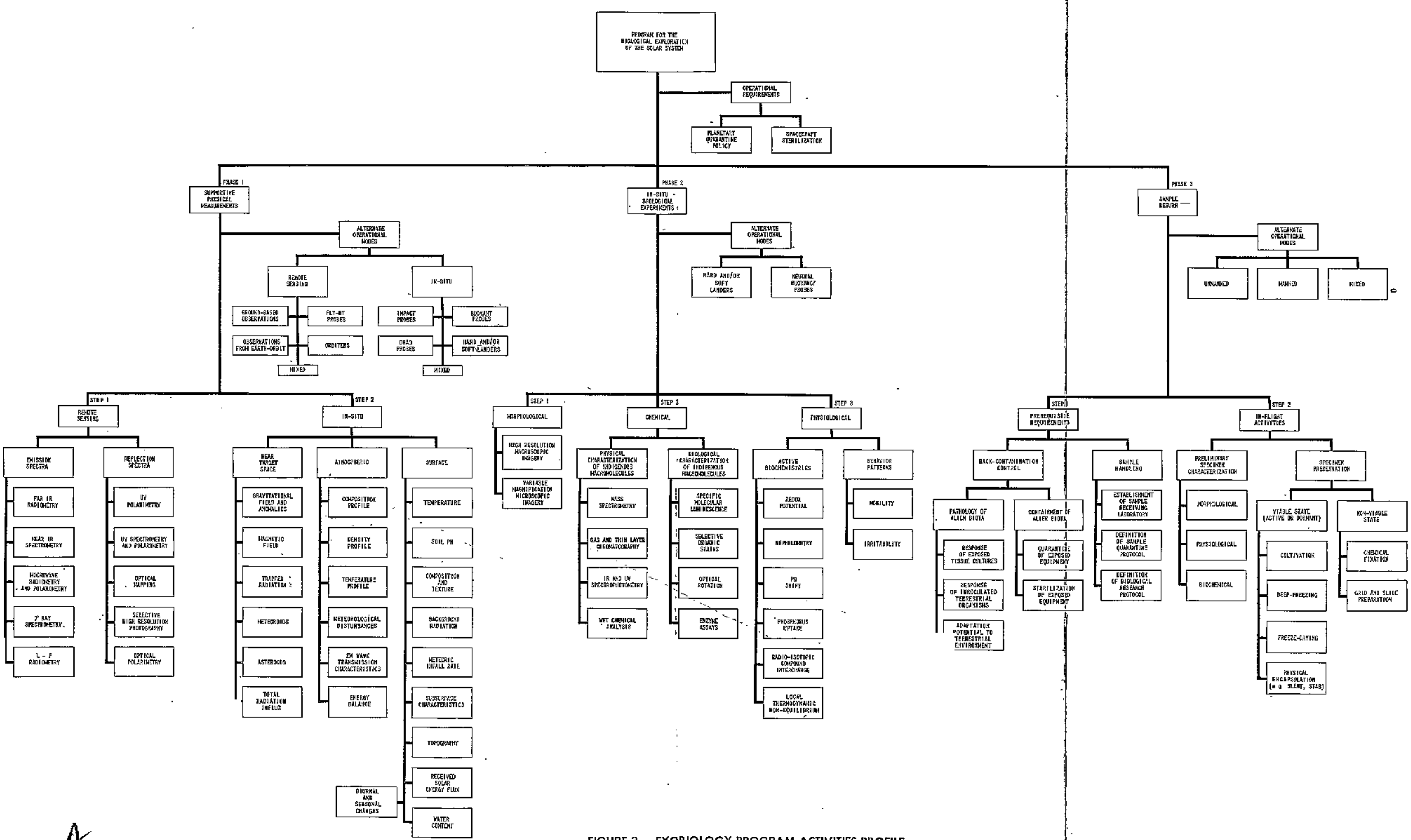

FIGURE 3 — EXOBIOLOGY PROGRAM ACTIVITIES PROFILE

A Foldout Frame 1 C Foldout Frame 2 B

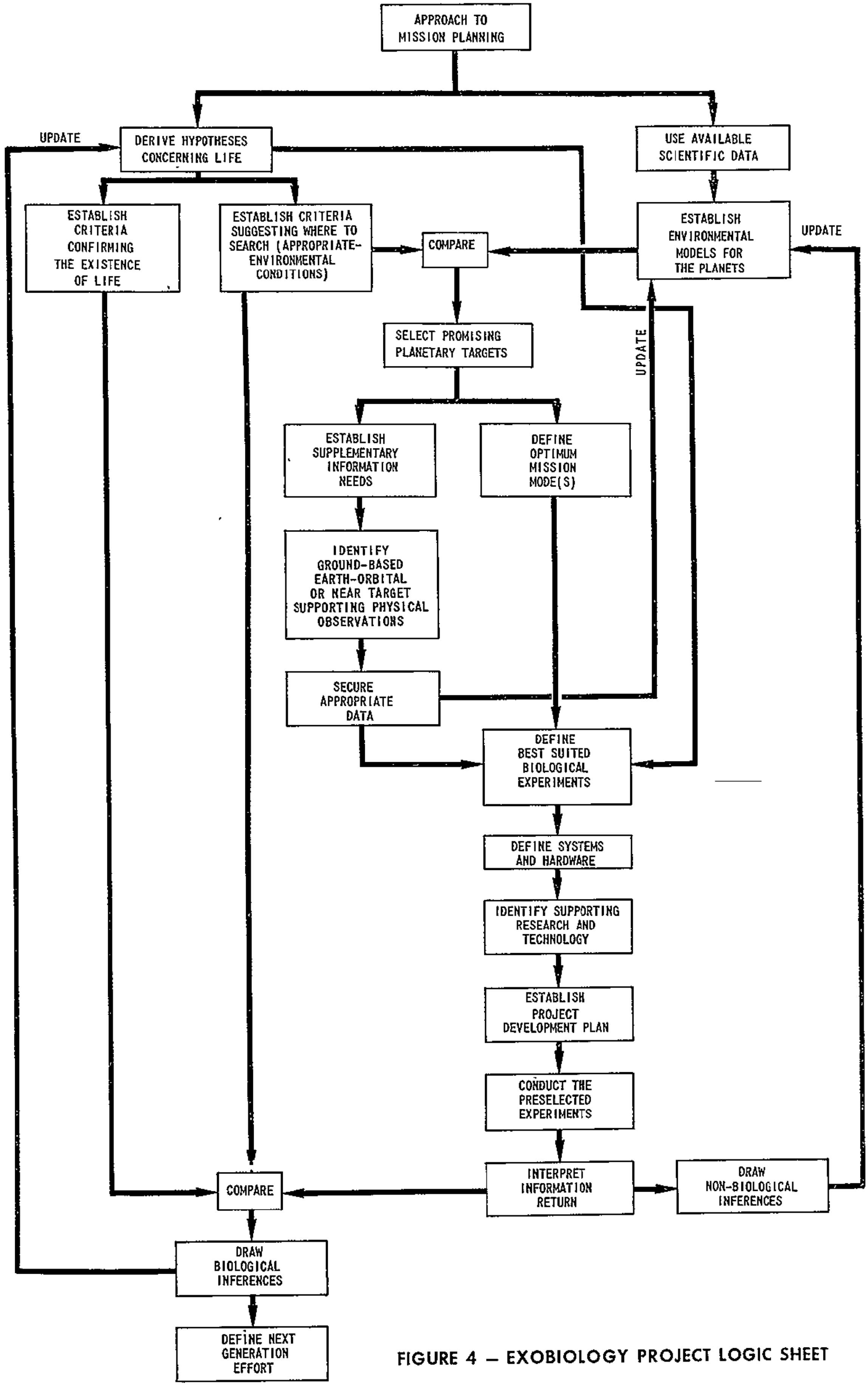

FIGURE 4 – EXOBIOLOGY PROJECT LOGIC SHEET

BELL SYSTEM