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Exobiology: Approaches to Life beyond the Earth

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It is a privilege to discuss some basic problems in biology with an audience whose special concern is for the recent striking advances in the physics of the earth in the solar system. However, many of us are looking forward to the close investigation of the planets, and few inquisitive minds can fail to be intrigued by what these studies will tell of the cosmic distribution of life. To conform to the best of our contemporary science, much thoughtful insight, meticulous planning, and laboratory testing must still be invested in the experimental approaches to this problem. This may require international cooperation and also—perhaps more difficult—mutual understanding among scientific disciplines as isolated as biochemical genetics and planetary astronomy.

Many discussions of space exploration have assumed that exobiological studies might await the full development of the technology for manned space flight and for the return of planetary samples to the terrestrial laboratory. To be sure, these might be preceded by some casual experiments on some instrumented landings. One advantage of such a program is that time would allow exobiological experiments to be planned with composure and deliberation. Undoubtedly, this planning would be more rigorous insofar as it was based on improved knowledge, from closer approaches, of the chemistry and physics of planetary habitats. Unfortunately, this orderly and otherwise desirable program takes insufficient account of the capacity of living organisms to grow and spread throughout a new environment. This unique capacity of life which engages our deepest interest also generates our gravest concerns in the scientific management of missions beyond the earth. On account of these, as well as of the immense costs of interplanetary communication, we are obliged to weigh the most productive experiments that we can do by remote instrumentation in early flights, whether or not manned space flight eventually plays a role in scientific exploration.

Motivations for Exobiological Research

The demons which lurk beyond the Pillars of Hercules have colored the folklore and literature of ages past and present, not always to the benefit of fruitful exploration and dispassionate scientific analysis. Apart from such adventuresome amusements and the amateur delights of a cosmically en-

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larged natural history, how does exobiology relate to contemporary science and culture? The exploration of space may seem to have very little to do with fundamental questions in biology or medicine, with the role of genes in embryological development, protein synthesis, the biology of viruses, and the evolution of species. The physical sciences may sharpen our perspective. Twenty-five centuries of scientific astronomy have widened the horizons of the physical world, and the casual place of the planet Earth in the expanding universe is a central theme in our modern scientific culture. The dynamics of celestial bodies, as observed from the earth, is the richest inspiration for the generalization of our concepts of mass and energy throughout the universe. The spectra of the stars likewise testify to the universality of our concepts in chemistry. But biology has lacked tools for such extension, and "life" until now has meant only terrestrial life. This disparity in the domains of the physical versus the biological sciences attenuates most of our efforts to construct a theoretical biology as a cognate of theoretical physics or chemistry. For the most part, biological science has been the rationalization of particular facts, and we have had all too limited a basis for the construction and testing of meaningful axioms to support a theory of life. At present, perhaps the only potentially universal principle in biology is the Darwinian concept of evolution through the natural selection of random hereditary fluctuations.

Some chemical attributes of terrestrial life might support a claim to be basic principles: for example, polyphosphates (adenylpyrophosphate) occur in all organisms as coupling agents for the storage and transfer of metabolic energy. But, at least in principle, we can imagine that organisms may have found alternative solutions to the same problem. Only the perspective of comparative biology on a cosmic scale could tell whether this device is an indispensable element of all life or a particular attribute of its local occurrence on this planet.

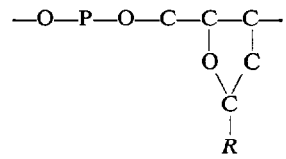
An important aim of theoretical biology is an abstract definition of life. Our only consensus so far is that such a definition must be arbitrary. If life has gradually evolved from inanimate matter, the demarcation of chemical from biological evolution is one of useful judgment. For a working principle, we might again rely upon the evolutionary concept: a living system has those properties (of self-replication and metabolism) from which we may with more or less confidence deduce an evolutionary scheme that would encompass self-evidently living organisms. But I do not propose this as a rote formula for the assessment of life on other celestial bodies, and certainly not before we have some empirical knowledge of the diversities of chemical evolution.

From this standpoint, the overriding objective of exobiological research is to compare the over-all patterns of chemical evolution of the planets, stressing those features which are globally characteristic of each of them.

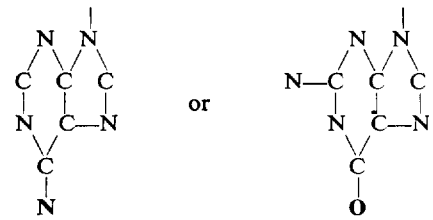
We are all thinking of the question: "Is there life on Mars?" To answer it may require a careful reassessment of our meaning of "life" and matching this with the accumulation of hard-won evidence on the chemical composition of that planet. On the other hand, we might be confronted with an object obviously analogous to an earthly plant, animal or microbe. But even this abrupt answer would be trivial in deference to a biochemical analysis of the organism and of its habitat for comparison with the fundamentals of terrestrial life.

In our first approaches to the nearby planets we will wish to design experiments which have some tangible foundation in the present accumulation of biochemical knowledge. The aqueous environment, and its corollary of moderate temperatures in which large carbonaceous molecules are reasonably stable, are implicit in terrestrial biochemistry. This is not to reject the abstract possibility of nonaqueous life, or noncarbonaceous molecules that might characterize temperatures of $< 200°$ or $> 500°K$. However, we can defer our concern for such exotic biological systems until we have got full value from our searches for the more familiar, and have learned enough of the exotic chemistry to judge how to proceed.

Within the bounds of its aqueous environment, what are the most nearly universal features of terrestrial life? In fact, our plants, animals, and bacteria share a remarkable list of biochemical components, and a biochemist cannot easily distinguish extracts of yeast cells and beef muscle. Among these components, the nucleic acids warrant first attention. Although they constitute the hereditary material, so that all the variety of terrestrial life can be referred to subtle differences in the nucleic acids, the same basic structure is found in the nuclei of all cells. This a long, linear polymer fabricated from a sugar-phosphate repeating unit:

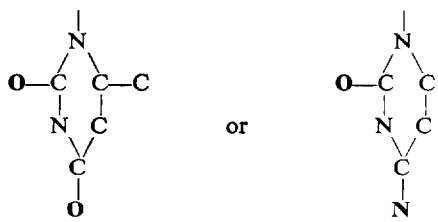


where R is a purine side group:



Adenine or Guanine

or a pyrimidine side group:

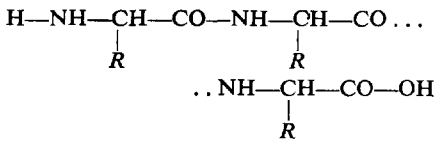


Thymine or Cytosine

The meaningful variety of nucleic acids depends on the specific order of the side group attached to each sugar on this monotonous backbone, a linear message written in a language of four letters, A, G, T, and C. The bacteria, which are the simplest free-living organisms, contain nucleotide sequences about 5 million units long; man contains sequences about 5000 million units long—this content being one of our best objective measures of biological complexity. On the other hand, the simplest viruses, which can multiply only inside living cells and come close to being single genes, have about 2500 units per particle. Playing a central role in the unification of terrestrial biology, nucleic acids underlie both heredity and (through their control of protein synthesis) development. Are they the only linear polymers which can subsume these functions, or have many other fundamental types evolved, to be found on other celestial bodies?

Equally general among the constituents of living cells are the proteins, which are also polymers, but with a more diverse set of constituents, some

20 amino acids. The fundamental backbone of a protein is a poly-amino acid chain:



where R may be any of 20 different groups, distinguishing a like number of amino acids found in natural proteins. Proteins assume a wide variety of three-dimensional shapes, through coiling and cross-linking of the polymer chains. They are in this way suited to perform such diverse functions as those of enzymes, structural elements, and antibodies. Not only do we find just the same 20 amino acids among the proteins of all terrestrial organisms but these are all the levo- isomers, although dextro- amino acids are found to have other metabolic functions. Next only to the incidence of nucleic acids, we would ask whether exobiota make analogous use of proteins, comprising the same amino acids, in hopes of understanding what seem to be random choices in the sculpture of our own living form.

Common to all forms of terrestrial life are also a number of smaller molecules which are involved in the working metabolism of the cells; for example, most of the B vitamins have a perfectly general distribution. They are vitamins for us only because we have learned, in our evolutionary history, to rely on their production by green plants, rather than to synthesize them within our own cells. But once formed, these vitamins, and similar categories of substances such as porphyrins, play entirely analogous roles in the metabolism of all cells.

A few substances, such as the steroid hormones, do play special roles in the metabolism of higher organisms, and testify to some progress in biochemical evolution. In fact, most objective evidence points to a loss of specific functions—microorganisms are certainly more versatile and less dependent than man is on a specific nutrient mileu. The main trend of biochemical evolution, from microbe to man, has been far less the innovation of new unit processes than the coordination of existing processes in time and space.

While we propose to give first priority to these most general questions, they by no means exhaust our interest in the peculiarities of extraterrestrial organisms, any more than they would for a newly discovered phylum of the earth's own repertoire. Nor should we preclude the possibility of finding new organisms that might be economically useful to man, just as new organisms were among the most fruitful yields of geographic exploration. However, the enlargement of our understanding, rather than of our zoos and botanical gardens, is surely our first objective.

Theories of the Origin of Life

At this point, a consideration of contemporary theory on the origin of life is justified for two reasons: (i) exobiological research gives us a unique, fresh approach to this problem, and (ii) we can find some basis to conclude that life need not be so improbable an evolutionary development as had once been supposed.

The interval between Pasteur's work on spontaneous generation and the recent past has been especially difficult for the mechanistic interpretation of the origin of life. Before Pasteur's time, many investigators could believe that simple microorganisms arose spontaneously in nutrient media. His demonstration that such media remained sterile if properly sterilized and protected seemed to rule out any possibility of "spontaneous generation." His conclusion was, of course, overdrawn, since life must have evolved at least once, and the event could still occur, though very much less frequently than had been supposed before. Meanwhile, the problem was compounded by the growth of biochemical knowledge. We now realize that bacteria, small as they are, are still extremely complex, well-ordered, and representative organisms. The first organisms must have been far simpler than present-day free-living bacteria.

With the growth of genetics since 1900, and the recognition of the self-replicating gene as the elementary basis of life, the question could focus on the origin of the first genetic molecule: given the power of self-replication, and incidents of stochastic variation, Darwin's principle could account for the eventual emergence of any degree of biological complexity.

An immense amount of fruitful genetic work was done in a period when "genetic molecule" was an abstraction and "self-replication" was an axiomatic principle whose chemical basis seemed beyond the grasp of human understanding. Now we recognize that the nucleic acids are the material basis of heredity, and we can begin to construct mechanistic models of their replication. The first principle, as already stated, is that the gene is a string of nucleotides, each position in the string being marked by one of the four nucleotide units A, T, C, and G. The polymerization of such strings by the union of the monomeric units presents no fundamental problems, but self-replication would necessitate the assembly of the units in a specific order, the one dictated by the order of the nucleotides in the parent molecule. The key to the solution of this problem was the realization by Watson and Crick that the complete nucleic acid molecule is a rigid, duplex structure in which two strings are united. In that rigid structure, as can be shown by suitable molecular models, adenine occupies a space which is just complementary to that of thymine, and cytosine is likewise complementary to guanine. A string can therefore replicate—that is, direct the assembly of another daughter string—in the following way. The nutrient mix of the cell contains all four nucleotide units. However, at any position of the parent nucleic acid molecule only one of these four can make a suitable fit and will therefore be accepted. After being accepted, the daughter units are firmly bound together by new chemical linkages giving a well-defined daughter string. Kornberg has reconstructed most of these events in some detail, by means of extracts from bacteria, to the very verge of proving duplication of genes in a chemically defined system in the test tube.

However, the media in which such syntheses can occur, in the cell or even in the test tube, are extremely complex. Knowing that the simplest organisms would be the most dependent on their environments for raw materials, where did these precursors come from before living organisms had evolved the enzymes to manufacture them?

Thanks to the insight of Haldane, Oparin, Horowitz and others, we now realize that this paradox is a false one, though it dates to the confusion between "carbon chemistry" and "organic chemistry" which still exists in English terminology. In fact, in 1828, Wöhler had already shown that an organic

compound, urea, could be formed experimentally from an inorganic salt, ammonium cyanate. A hundred years later, a number of routes for synthesis of geochemically significant amounts of complex organic materials were pointed out, for example, the hydrolysis of metallic carbides, and subsequent reactions of olefins with water and ammonia. More recently, Miller and Urey demonstrated the actual production of amino acids by the action of electric discharges on gas mixtures containing the hydrides NH_3, OH_2, and CH_4. This demonstration converges with other argument that the primitive atmosphere of the earth had just such a reduced composition, becoming oxidized secondarily (and in part through photosynthetic separation of carbon from oxygen).

An alternative theory of origin of carbonaceous molecules is even more pervasive. Perhaps we associate carbon with life, and rocks and metals with physical phenomena; beyond doubt we tend to connote the latter with the predominant substance of the universe. In fact, as a glance at tables of cosmic abundance will show, the lighter elements are by far the most prevalent, and after the dispersed hydrogen and helium these are carbon, oxygen, and nitrogen. The primitive condensation of free atoms to form the interstellar smoke, and eventually the stars themselves, must entail the molecular aggregation H + C + O + N; that is, a large fraction of the condensed mass of the universe must consist, or once have consisted, of organic macromolecules of great complexity. The chief problem for their synthesis is in fact not a source of chemical energy but how to dissipate the excess energy of reactions of free atoms and radicals.

This aspect of astrophysics may have place for a remote biological analogy: Once a few molecules have formed, the energy of subsequent impacts can be dissipated among the vibrational degrees of freedom. That is, such molecules can function as nuclei of condensation. As seeds for further condensation, those molecules will be favored which (i) most readily dissipate the energy of successive impacts and (ii) can undergo molecular fission to increase the number of nuclei. The actual molecular chemistry of the interstellar (or prestellar) smoke is thus subject to a kind of natural selection and cannot be a purely random sampling of available atoms.

Whether the earth has retained remnants of this chemistry is hard to say. There is at least some evidence of it in the spectra of comets, and fragments from these continue to form part of the meteoroidal infall. These particles, unless associated with larger meteorites, would be unrecognizable after traversing the earth's atmosphere; they are among the possible treasures to be found buried in protected crevices on the moon.

Light traversing the interstellar smoke has been found to be polarized. If primitive aggregation plays some role in furnishing precursors for biological evolution, this polarization furnishes at least one bias for a decision between levo- and dextro- isomers.

At any rate, possible sources of probiotic nutrition no longer pose a problem. Before the appearance of voracious organisms, organic compounds would accumulate until they reached equilibrium with thermal and radiative decomposition, from which the oceans would furnish ample protection. Locally, the concentration of the soup would be augmented by selective evaporation, and by adsorption onto other minerals. The main gap in the theory, not yet bridged by any experiment, is the actual formation of a *replicating* polymer in such a morass. We are beginning to visualize the essential conditions for chemical replication, and its ultimate realization is foreshadowed both by biochemical studies of nucleic acids and by industrial syntheses of stereospecific polymers.

There is some controversy over whether nucleic acids were the first genes, partly because they are so complex, partly because their perfection hints at an interval of chemical evolution rather than one master stroke. The advantage of the nucleic acid hypothesis is that no other self-replicating polymers have so far been found. But, as an alternative speculation, a simplified protein might replicate by the complementary attachment of acidic versus basic units, perhaps the crudest possible method of assembly. The nucleic acids would be perfections on this theme for replication. The existent proteins do not replicate; with their variety of amino acids, they would have evolved as better adaptations for assuming specific shapes. A comparative view of independent evolutionary systems may at least serve to check such speculations.

Although many steps in the generation of living molecules remain to be re-created, we can state this as a relevant problem for exobiological study, with considerable optimism for the prevalence of life elsewhere. But a sterile planet, too, would be of extraordinary interest to biology for the insight it should give on the actual progress of probiotic chemical evolution.

Natural and Artificial Panspermia

In the foregoing discussion it was tacitly assumed that the evolution of planetary life was a local phenomenon, independent of the incidence of life elsewhere. But, at a time when *de novo* generation seemed less plausible than it does now, Arrhenius defended another hypothesis: *panspermia,* the migration of spores through space from one planet to another. The credibility of the panspermia hypothesis has been eroded mainly for two reasons: (i) the lack of a plausible natural mechanism for impelling a spore-bearing particle out of the gravitational field of a planet as large as the earth, or any planet large enough to sustain a significant atmosphere, and (ii) the vulnerability of such a particle to destruction by solar radiation. In any case, the panspermia hypothesis could be disparaged for evading the fundamental problem by transposing it to an unknown, perhaps scientifically unknowable, site. These difficulties have impeached the standing of panspermia as an experimentally useful hypothesis, but not its immense significance for cosmic biology. In its defense, it might be indicated that, in view of the dormancy of microorganisms in high vacuum and at low temperatures and of their relatively low cross section for ionizing radiations, the hazards of exposure to space may have been exaggerated. The chief hazard to microorganisms might come from solar ultraviolet radiation and the proton wind, but a thin layer of overlying material would shield a spore from these. For the impulsion of particles we might possibly appeal to impacts with other heliocentric bodies, be they grazing meteorites or planetoids in cataclysmic encounters—suggestions not more remote than those invoked for other astronomical phenomena. Nor can we be sure that all the electrokinetic mechanisms which Arrhenius may have had in mind can be excluded from applying to any single particle.

In testing for panspermia, we would be concerned first of all for evidence of interplanetary transport of any material. The moon suggests itself as a nearby trap for particles of terrestrial origin, among which living spores or biochemical fragments of them, might be the most characteristic markers. At one spore per kilogram of sample (a weight ratio of 10^{-15}), the sensitivity of easy biological detection would partly compensate for the vulnerability of spores to physical hazards.

The development of rocket-impelled spacecraft has, of course, furnished a mechanism for producing artificial panspermia. Several authors have recently revived Haldane's passing suggestion that life might even have been disseminated by intelligent beings from other stellar systems. That another century of productive science and technology could give the human species this capability would be hard to dispute. The hypothesis is connected with the age or agelessness of the universe, and until we have a basis for decision on this point, and can make independent tests for intelligent life elsewhere, it must join natural panspermia in the limbo of irrefutable, untestable scientific hypotheses. The technique for attempted radio communication with nearby stars has been detailed recently by Cocconi and Morrison.

These new tools for the exploration of the universe have caught many of us unawares, and few can pretend to have recaptured their equilibrium in dealing with these concepts. Irrefutable notions have little scientific value unless they lead to attempts at verification. A priori arguments for the presence or absence of intelligent life on the planets or in nearby stellar systems are equally unconvincing. The skepticism of most scientists is justified not by conviction but by the consistency of negative evidence in the limited scientific data that have so far been collected.

Planetary Targets

The suitability for life of the accessible bodies of the solar system has already received ample attention. Mars is, of course, the likeliest target, most nearly resembling the habitat of the earth. The indicated scarcity of free moisture and oxygen would severely limit the habitability of Mars by man or most terrestrial animals. However, there seems little doubt that many simpler, earthly organisms could thrive there. Indeed, many students have concluded that Mars does have a biota of its own. The most pertinent evidence is perhaps the infrared reflection spectrum recorded by Sinton which indicates an accumulation of hydrocarbonaceous materials in the dark areas. This is complemented by Dollfus' report (see this symposium) on the seasonal changes of granularity of these areas. The main reservation that must be registered is that these might be meteorological phenomena involving masses of material which may be carbonaceous but not necessarily living. Most such material on the earth's surface is associated with life. However, this may be connected with the greedy utilization of such compounds by organisms rather than their production by vital synthesis. However, the most plausible explanation of the astronomical data is that Mars is a life-bearing planet. (The term *vegetation* is often used; this should be discouraged if it implies that the Martian biota will necessarily fall into the taxonomic divisions that we know on earth.)

The habitability of Venus is connected with its temperature, a highly controversial subject. Perhaps the most useful first contribution to the exobiology of Venus would be a definitive measurement of its temperature profile. Even should the surface be unbearably hot, this need not preclude a more temperate layer at another level.

The exposure of the moon's surface to solar radiation and the absence of a significant atmosphere have led scientists to discount the possibility of a lunar biology. However, the composition of the moon's deeper layers, below even a few meters beneath the surface, is very much an open question (see Urey, this symposium) particularly in the light of Kozyrev's recent reports of gaseous emissions. Realistic plans for the biological study of the moon probably must await the results of chemical analyses. Apart from the remote possibility of indigenous life, the moon is a gravitational trap for meteoroidal material. We may eventually be able to screen large quantities of this virgin material for what Haldane called astroplankton, in an empirical test of the panspermia hypothesis. While exposed deposits would be subject to solar degradation, shaded refuges must also exist. Mercury may be analogous to the moon, except insofar as its dark side may furnish an even more reliable, though much more remote, refuge of this kind.

It may be academic to discuss the exploration of the major planets, in view of their distance and the difficulty of deceleration in the Jovian field. However, their wealth of light elements, subject to solar irradiation at temperatures and in gravitational fields very different from the earth's, offers the most exciting prospects for novel biochemical systems.

Experimental Approaches

A realistic view of our limitations requires that our treatment of this topic be one of utmost humility. Useful landings on planetary targets are fraught with difficulties and hazards, and experiments done at a distance must not be overlooked in the excitement of planning for more adventurous missions. Balloon- and satellite-mounted telescopes can tell much about planetary chemistry, and hence biology, and probes to the vicinity of a planet can furnish additional information prior to actual landing.

It is instructive to ask ourselves how we might diagnose the existence of life on the earth from distant observations. If we may judge from the photographs so far obtained from high-altitude flights, we could hope to detect only large-scale manifestations of organized culture—cities, roads, rockets. This reserve may not give due credit to the possibilities of high-resolution photography and sensitive infrared spectrometry, and reasonable implications from seasonal changes in the color and texture of terrain. However, we may conclude that distant approaches will be invaluable for deriving preliminary chemical information but probably will not be decisive for exobiological inferences. Even if we could more surely decide that the Martian cycle involved living organisms rather than inanimate chemical transformations, we would still have little insight into the intimate biochemical details which are a major objective of exobiological research. On the other hand, a planet could harbor an extensive biota that would defy detection from a distance, like the biota of our own extensive deserts and deep waters.

Microorganisms, for many reasons, are the best prospects on which to concentrate marginal capabilities. They are more likely to flourish in a minimal

environment than larger organisms. The microbes must also precede the macrobes in evolutionary sequence, though we must not suppose that present-day bacteria are necessarily very primitive. The earth is well endowed with both kinds of organisms; we can imagine another world with only microbes, but we cannot conceive of one lacking microbes if it bears any form of life at all. Likewise, taking the earth as a whole, we find that large organisms occupy only a small fraction of the surface. However, we can reasonably expect to find evidence of microscopic life in any drop of water, pinch of soil, or gust of wind. Given a limited sample for study, microbiological analysis will certainly give the most reliable evidence for the presence of life anywhere on the planet. By the same odds the greatest diversity of biochemical mechanisms will be represented among the microbiota of a small sample.

Microbiological probes also offer distinct advantages for the collection and analysis of living material. From a single particle, microbes can easily be cultivated within the confines of an experimental device. In this they remain accessible to physiological and chemical experiments that would be extremely cumbersome with larger organisms. (Compare, for example, the automatic instrumentation that would be needed to catch a mouse or an elephant and then to determine its nutritional requirements!). The techniques of cytochemistry already developed for the chemical analysis of microscopic cells and organisms appear to be the most readily adaptable to automation and telemetric recording, an important advantage under the existing pressure of time, talent, and cost. Important issues of policy cannot be decisively settled without factual information on the growth capacity of the microorganisms that might be exchanged among the planets. Accordingly, methodological precedents in terrestrial science for exobiology are most evident in microbial biochemistry. The conceptual aims are equally close to those of biochemical genetics. Needless to say, no other resource or objective of serious biological science can be neglected in the development of an experimental program.

Aside from experimental designs, the pace of exobiological research may be regulated by advances in vehicular and guidance capabilities and data communication. In the expectation that these will remain in reasonable balance —for static or real time television communication with the planetary probe— the microscope may be the most efficient sensory instrument. The redundancy of a pictorial image would not be altogether wasted: would we put our trust in a one-bit pulse from an efficient black box to answer our queries about the cosmos?

According to this experimental concept, the terminal microscope-Vidicon chain must be supported by three types of development: (i) for collection and transport of the specimen to the aperture of the microscope; (ii) for cytochemical processing of the samples; (iii) for protection of the device against environmental hazards, for appropriate location after landing, and for illumination, focusing, and perhaps preliminary image selection. Detailed studies of these problems are only just under way, and the following suggestions are only tentative.

The easiest specimens to obtain may be atmospheric dust and samples of surface soil, once the device has been landed. These would be collected on a traveling ribbon of transparent tape which would be thrown out and then rewound into the device. Larger samples, collected by a soil auger, could be subjected to a preliminary concentration of nonmineral components by flotation in a dense liquid. The use of such a tape would simplify the problem of treating the samples with a succession of reagents—for example, specific enzymes and fluorescent stains for the detection of nucleic acids and proteins. Microscopy with ultraviolet light, particularly at 2600 and 2800 angstroms, owing to its selectivity for nucleic acids and proteins, may be the most direct way to distinguish microorganisms from mineral particles. Generally speaking, the microscope can be adapted to many simple analytical procedures whose construction on a larger scale would present formidable problems for automatic technique.

The adaptation of the microscope system to a payload can be undertaken more realistically when laboratory prototypes have been built and tested. For example, we will have to decide between accurate prefocusing of a microscope whose lenses and entry slit are mounted in a rigid structure and continuous control of focus by an optically controlled servo system (an innovation that would be far from useless in the biological laboratory). Fluorescent staining may facilitate automatic discrimination for conservation of radio power; the traveling ribbon can be stopped and the Vidicon-transmitter activated just when a stained object is in view.

These preliminary experiments can indicate some of the general features of the planetary microbiota. The data they furnish will support more intensive studies of the growth characteristics, chemical composition, and enzymatic capabilities of organisms cultivated on a larger scale. The interaction of these organisms with tissue cultures of animal cells can also be considered. From the results of these initial probes we can better deduce how to anticipate the long-range consequences of the intercourse of planetary biota.

Conservation of Natural Resources

A corollary of interplanetary communication is the artificial dissemination of terrestrial life to new habitats. History shows how the exploitation of newly found resources has enriched human experience; equally often we have seen great waste and needless misery follow from the thoughtless spread of disease and other ecological disturbances. The human species has a vital stake in the orderly, careful, and well-reasoned extension of the cosmic frontier; how we react to the adventuresome and perplexing challenges of space flight will be a crucial measure of the maturity of our national consciences and our concern for posterity.

The introduction of microbial life to a previously barren planet, or to one occupied by a less well-adapted form of life, could result in the explosive growth of the implant, with consequences of geochemical scope. With a generation time of 30 minutes and easy dissemination by winds and currents, common bacteria could occupy a nutrient medium the size of the earth in a few days or weeks, being limited only by the exhaustion of available nutrients. It follows that we must *rigorously* exclude terrestrial contaminants from our spacecraft. This stricture must hold until we have acquired the factual information from which we can assess with assurance the detrimental effects of free traffic and determine whether these are small enough to warrant the relaxation of these controls.

At the present time, the values that would most obviously be threatened by contamination are scientific ones. The overgrowth of terrestrial bacteria on

Mars would destroy an inestimably valuable opportunity for understanding our own living nature. Even if an intemperate mission has not contaminated a planet, the threat of its having done so will confuse later studies, if earth-like organisms are found. However, other values are also involved. Quite apart from strictly scientific concerns, would we not deplore a heedless intrusion on other life systems? It would be rash to predict too narrowly the ways in which undisturbed planetary surfaces, their indigenous organisms, or their molecular resources may ultimately serve human needs. If we have cause to prejudice these values, we surely would not wish to do so by inadvertence.

To guard effectively against contamination requires a nice appreciation of the ubiquity and durability of bacterial spores, which are well preserved in high vacua and at low temperatures and are rapidly destroyed only when kept at temperatures over 160°C. It is probable that spacecraft can be disinfected by the conscientious application of gaseous disinfectants, especially ethylene oxide, but this will succeed only if the procedure is carried out meticulously and with controlled tests of its effectiveness. Sealed components, if found to be potential sources of contamination, can be disinfected by chemicals prior to sealing, or subsequently by heat, or by irradiation at very high doses. The technology of disinfection is an expert one, and personnel already experienced in it should be delegated supervisory control.

The assessment of this problem involves a concept of risk that has not always been perceptively realized. The hazards of space flight itself, or of hard impact, or the planetary environment *might* suffice to neutralize any contaminants, but can we afford to rely on uncertain suppositions when the stakes are so high, and when we have practical means at hand for conservative protection? We must be especially sensitive to the extreme variations in the environments of spacecraft or of planetary surfaces which might furnish refuges for microbe survival no matter how hostile the *average* conditions.

The indication by agencies both in the United States and the U.S.S.R. that adequate precautions will be exercised on all relevant missions is an important step in the realization of constructive exobiology.

Scientists everywhere will call for the application of these measures with the same care and enthusiasm as the more positive, exciting, and patently rewarding aspects of space research. Scientific microbiology in the laboratory is absolutely dependent on the rigorous application of the special technique of pure culture with aseptic control. If we do not exercise the same rigor in space science, we might as well save ourselves the trouble of thinking about, and planning for, exobiological research.

While early traffic to the planets will be one-way, we must anticipate round-trip, and even manned, space flight. Undoubtedly, planetary samples can be analyzed for any scientific purpose more conveniently and more exactly in the terrestrial laboratory than by remote devices. For each step of analysis, special devices can be used (or if need be, newly designed and constructed), and a constant give-and-take between human judgment and instrumental datum is possible. However, the return of such samples to the earth exposes *us* to a hazard of contamination by foreign organisms. Since we are not yet quite certain of the existence of planetary (that is, Martian) organisms, and know nothing of their properties, it is extremely difficult to assess the risk of the event. The most dramatic hazard would be the introduction of a new disease, imperiling human health. What we know of the biology of infection makes this an extremely unlikely possibility; most disease-producing organisms must evolve very elaborate adaptations to enable them to resist the active defenses of the human body, to attack our cells, and to pass from one person to another. That a microorganism should have evolved such a capacity in the absence of experience with human hosts or similar organisms seems quite unlikely. However, a converse argument can also be made, that we have evolved our specific defenses against terrestrial bacteria and that we might be less capable of coping with organisms that lack the proteins and carbohydrates by which they could be recognized as foreign. Furthermore, a few diseases are already known (for example, psittacosis, botulism, aspergillosis) whose involvement of man seems to be a biological accident. These arguments can only be resolved by more explicit data. Nonetheless, if they are harmful at all, exobiota are more likely to be weeds than parasites, to act on our agriculture and the general comfort of our environment, and to be pervasive nuisances than acute aggressors. However, even the remotest risk of pandemic disease, and the greater likelihood of serious economic nuisance, must dictate a stringent embargo on the premature return of planetary samples, or of craft that might inadvertently carry them. Again, our preliminary experiments must give us the foundation of knowledge to cope with exoorganisms, even to select those which may be of economic benefit. A parallel development of techniques for disinfection may mitigate some of these problems; at present the prospects for treating a returning vehicle to neutralize any possible hazard are at best marginal by comparison with the immensity of the risks.

Of the possible payloads for interplanetary travel, living man, of course, excites the widest popular interest. In due course, he may be supported by a sufficient payload to accomplish useful tasks in exploration beyond the capacities of instrumentation. However, he is a teeming reservoir of microbial contamination, the most difficult of all payloads to neutralize, and he is an especially suitable vehicle for infectious organisms. In view of these difficulties, and insofar as manned space flight is predicated on the return of the crew, a sound basis of scientific knowledge from instrumented experiments is a *sine qua non* for the planning of such missions.

Timely effort now to devise and build instrumented experiments is essential to keep pace with the technical capacities of space vehicles.

Conclusion

Many of the ideas presented in this article are not new. In the scientific literature they have been treated only occasionally, for example in a remarkable article by J. B. S. Haldane (1954). They are also anticipated in the classic works of science fiction—for example, H. G. Wells' *War of the Worlds*—and in a flood of derivative fantasies of less certain quality either as science or as fiction. This kind of attention has not necessarily contributed to realistic evaluation of the biological aspects of space travel, discussion of which may still be dismissed as overimaginative by some of our colleagues. However, exobiology is no more fantastic than the realization of space travel itself, and we have a grave responsibility to explore its implications for science and for human welfare with our best scientific insights and knowledge.

Notes

The principles embodied in this article reflect the judgment of one among several of the scientific groups advisory to the Space Science Board of the U.S. National Academy of Sciences. However, they do not necessarily represent any official policy of the committed views of each consultant. The continued interest and advice of M. Calvin, R. Davies, N. Horowitz, S. E. Luria, A. G. Marr, D. Mazia, A. Novick, C. Sagan, G. Stent, H. C. Urey, C. B. van Niel, and H. Weaver, among many others, have been indispensable.

To document this article in detail with references to original sources would require a bibliography of inordinate length. Many of the issues are reviewed in the following works.

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