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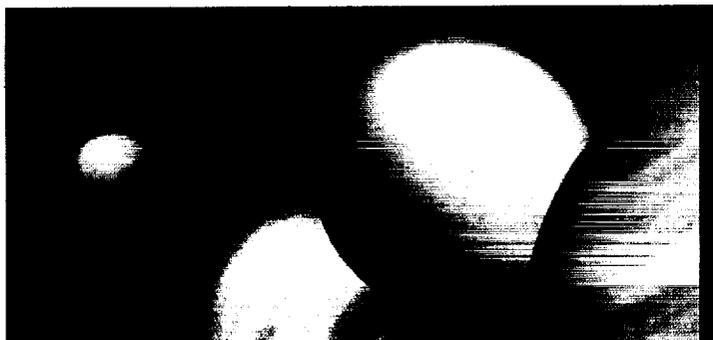
The Solar System: Importance of Research to the Biological Sciences

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Even as the two Viking Landers touched down to begin their experiments on the Martian surface in 1976, many of those who were skeptical about finding life on Mars were proclaiming that the biologists associated with space research would soon be "out of business"; that the search for extraterrestrial life would prove to be negative (at least within our solar system); and that, therefore, there would be no further interest in pursuing the subject of exobiology. Indeed, as the data from the Vikings accumulated and were analyzed, the prospects for extant life on Mars became remote, as did the likelihood of studying extraterrestrial organisms.

It was almost 30 years ago that Joshua Lederberg coined the term "exobiology" to describe the then-new scientific enterprise (more or less loosely defined as the study of extraterrestrial life). While Lederberg made it abundantly clear that the actual search for extraterrestrial life was

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part of the larger question of how life arises from inanimate matter, to many, exobiology came to be synonymous with the *search* for extant life on other planets. Such was, and still is, the view of many individuals who do not understand the biological context within which the search for life on Mars was carried out.

What needs emphasis is that the Viking Mission was, for biologists, an important test of our ideas on how life arises from primordial nonbiological materials. In retrospect, we were probably naive in our assumptions about the ease with which replicating organic systems are formed and evolve on a planetary body. The Viking results have emphasized how much more we need to know about the history of chemical and biological evolution.

Exobiology today involves scientists from a wide variety of disciplines—from astronomy to molecular biology—all contributing to the common goal of understanding how matter in the universe evolves toward replicating systems—i.e., toward life. In essence, we are trying to understand the *course of evolution*—going backward in time to the origins, in stars, of the biogenic elements necessary for life; through the subsequent processing of these elements in the interstellar medium

and on planetesimals and planets, to yield organic compounds; and, ultimately, to the appearance of replicating organic molecules. In extensions of this evolutionary theme, exobiology also encompasses inquiry into the earliest stages of *biological evolution* and how the evolution of biological systems is affected by the physical evolution of a planetary body.

It is important to realize that the goal of understanding the course of chemical and biological evolution will not only require intensive study of the Earth and a more complete history of terrestrial organisms, *but will also require critical data that exist elsewhere in the solar system.*

The Role of Space Missions

During the past two decades, we have seen important advances in the study of chemical evolution which provide ample laboratory experimental verification that very simple compounds can be transformed into organic matter of reasonable complexity. However, we are on tenuous grounds when we try to pin down these evolutionary processes in time and space.

In this regard, solar system missions have been important in helping us to understand the early environment of the Earth and the subsequent evolution of organisms. But there are still wide gaps in our knowledge of the processes that led to the origin of life and conflicting models of the environments within which biology, once initiated, first began to evolve. Many of these uncertainties can be substantially constrained by continued exploratory missions to objects in the solar system, several of which have surfaces and atmospheres that still retain information—lacking on the Earth—about the early history of the solar system.

History of the Biogenic Elements and Their Compounds

In tracing the history of organic chemical evolution prior to the formation of the solar system, one way in which space missions can contribute to this understanding is by the study of interplanetary dust particles. What is their composition? What is their relationship to interstellar and circumstellar grains which are believed to aggregate and ultimately condense to form new planets, and which are also known to contain organic compounds? It is important to understand any evolutionary relationships among these types of grains. Evidence has already been obtained suggesting that grains originating from pre-solar system sources can become incorporated into solar system planetesimals such as meteorites.

Characterization of the molecular complexity in these grains will require observations in the far infrared, visible, and ultraviolet regions of the electromagnetic spectrum. In addition, critical spectral regions will require

that observations be made using space-based instruments with high angular and spectral resolutions.

Another important area that can benefit from space missions is the actual collection of dust grains, taking advantage of devices on board a space station. In principle, it should be possible to separately collect interstellar and interplanetary particles for subsequent study. Furthermore, the possibility of collecting these in a nondestructive manner, to preserve volatiles and organic compounds, is an important objective for such investigations.

As we continue to trace the fate of grains containing the biogenic elements and organic compounds, it is important to learn how the incorporation of such grains and associated gases into the solar nebula may have affected preexisting organic compounds. Processes such as pyrolysis and evaporation could have caused their loss or destruction, while processes such as turbulence and radiation may have promoted the synthesis of organics. Almost certainly, further chemical modifications took place as the nebular dust grains accreted into larger objects, such as comets, asteroids, and planets.

What were the chemical processes that may have affected the biogenic materials during this phase of the formation of bodies in the solar system? To obtain insight into these processes, it would be highly desirable to understand the formation of grain aggregates. Studying some aspects of this process in the absence of gravity (for example, in a laboratory on a space station) can be a useful technique in this area.

Vital clues to the history of the biogenic elements also exist today in primitive solar system objects, including meteorites, comets, and asteroids. What are the detailed compositions of these bodies? What are the distributions of organic compounds in them? What interrelationships exist among the various classes of objects? What pre-solar phases can be identified in them? To answer these questions adequately, direct access is needed to these objects. This, in turn, will require a variety of *in situ* and sample return solar system missions. Among these, highest priority should be given to investigations of comets, particularly those comets likely to have preserved intact nebular gases and grains containing the biogenic elements and their compounds.

Early Planetary Environments and the Origin of Life

As we contemplate the processes on the primitive Earth leading to the origin of life, one major question revolves around the nature of the primordial atmosphere. How reducing were conditions on the Earth during that period? Was the atmosphere dominated by hydrogen, thus facilitating the abiotic synthesis of organic precursors necessary for life? For this, the giant outer planets—with their hydrogen-rich atmospheres—can provide a wealth of information on the nature of the chemistry that is possible under highly reducing natural conditions. For this reason, these planets represent prominent targets for exobiological study. What is the distribution of organic matter in these planets? More significantly, what is the origin of these compounds? To elucidate these questions, detailed *in situ* measurements will be required. For example, knowledge of the distribution with altitude of organic matter, carbon monoxide,

and phosphine in the atmospheres of Jupiter and Saturn—coupled with computer and laboratory simulation experiments—can lead to a better understanding of the chemistry that is taking place on these bodies.

The Saturnian satellite, Titan, is a special case for study in the outer solar system. Here too, extensive organic chemistry must be occurring, as evidenced by the large number of organics that have been identified in its atmosphere. What level of complexity is reached by organics on Titan? What is the chemistry that accounts for these? Without a doubt, atmospheric entry missions, such as the “Titan-Cassini” Mission, will be required in order to answer many of the questions about the organic components on Titan.

In addition to the dark surface revealed by the recent comet Halley encounter, dark coatings are also found on the surfaces of Phoebe, Iapetus, some of the outer-planet satellites, on some asteroids, and in the rings of Uranus. On all of these bodies there is thus the suggestion of carbonaceous matter. What is the relationship of these to each other and to the dark, carbonaceous, surface matter of meteorites rich in organic compounds, such as the Murchison meteorite? What is their mode of formation? For

the resolution of these questions, it will be necessary to obtain considerable new and sophisticated spectroscopic data concerning their composition. Some may come from ground-based observatories, but a more complete understanding will require spaceborne instruments and, ultimately, *in situ* and sample return missions.

One of the large unknowns surrounding the environment within which the first organisms arose has to do with the possible contribution by impacting bodies to the Earth’s inventory of volatiles and organic compounds. It is essential that we obtain better insight into this issue. When and how were the volatile materials necessary for life added to the Earth’s surface? To assess the role of cometary and asteroid impacts in the early history of the Earth, many problems need to be solved. We need to put better bounds on the input of cometary and asteroidal volatiles and organics, we need to model the size distribution of such impacting bodies on the primitive atmosphere and the effects of such impacts on the synthesis and destruction of organics, and we need to integrate this information with the most reasonable models of the primitive atmosphere

with regard to its redox characteristics.

These issues will require theoretical and experimental studies of the physics of cometary and meteoritic impacts in order to place limits on the survival rates of organic compounds, as well as thermochemical calculations of the composition of atmospheres produced by large impacts. High-sensitivity visible and infrared searches for comets in the Oort cloud would be highly desirable to determine the large end of the size distribution of objects that may have impacted the early Earth.

At present it is impossible to estimate the contribution of organic matter to the prebiotic Earth by impacting bodies. Equally difficult is the assessment of the nature of any organics that might have survived this process. Were the important precursor molecules for life formed subsequently? If so, how were the precursors of biological macromolecules synthesized on the prebiotic Earth? What mechanisms were involved? What were the first stages of molecular replication?

Of necessity, work in this area requires modeling the composition and history of the early terrestrial atmosphere and evaluating the early terrestrial environment with regard to other parameters, such as temperature, atmospheric pressure, solar radiation, etc.

For meaningful laboratory simulations of possible prebiotic processes for the synthesis of precursor molecules, the simulations must be carried out under conditions that are consistent with the most realistic models of the Earth at that time. *In turn, these models will be strongly dependent upon information gathered from solar system missions.*

Early Biological Evolution

When did the first stable biota appear on this planet? It is not at all clear whether the initial form of life may have been wiped out by some catastrophic event, only to arise again later—perhaps even several times—before more clement conditions were sustained on the Earth.

What environmental constraints must be placed on the early Earth for determining the timing of the origin of life and for the *maintenance* of the first organisms? Answers to these questions again will entail studies of the effects of impacting bodies on the post-accretionary Earth. Significant insights are also to be obtained from modeling studies to determine the biological effects of “rock vapor” and of “tsunamis” created by large-body impacts. Corollary analyses of lunar and Martian cratering data will help to provide limits on the size and frequency of such early large-body impacts. Additional critical geophysical and geochemical data will also be necessary, requiring analysis not only of ancient terrestrial rock samples, but also of rock samples from Mars.

Evolution of Cellular and Multicellular Life

Another area of evolutionary biology that is strongly dependent upon models of the terrestrial environment is one that deals with the evolution of the major biological groupings. It is now abundantly clear that biological evolution is closely linked to the physical evolution of this planet and that to understand biological evolution one needs to integrate the biological record with the physical record of the planet. What was the nature and what were the times of origin of the major groups of prokaryotic and eukaryotic organisms? What was the sequence of evolution of these organisms? Can we correlate the phylogenetic relationships among organisms with the geological record? Understanding how physical environmental factors may have driven the *early* biosphere will require detailed analysis of well-preserved sedimentary basins, particularly those of Archean and Proterozoic ages, for integrating the biological and geological records. Better constraints are needed on the temperature history of the Earth, on the history of the atmosphere, and on the chemistry of the oceans, as

well as on the history of solar radiation. Once more, studies in this field will depend upon valid models of the evolving Earth, and these will be derived, at least in part, from comparative planetology and from studies of the Sun.

Can we find, in the geological record, convincing evidence that cosmic events have influenced the course of biological evolution? To address this issue, studies are needed that will be directed toward the recognition of extraterrestrial (e.g., asteroidal, cometary) "signatures" in terrestrial sedimentary successions, as well as research to evaluate temporal patterns in the fossil record.

Importance of Mars

Of all the objects for study beyond the Earth, Mars assumes a position of prime importance for exobiological study. Based on knowledge derived from ground-based observations and from previous space missions, a vast amount of information has accumulated concerning the gross environmental characteristics of Mars. These indicate an environment that is relatively Earth-like when compared to other objects in the solar system. The information upon which this assessment is made is far from complete. Furthermore, considerably less is known about the early history of Mars. Nevertheless, it is reasonable to assume that Mars was accreted at about the same time, out of essentially similar materials, as was the Earth, and that the subsequent cosmic influences on Mars (e.g., solar radiation and cometary and asteroidal impacts) closely paralleled those felt by Earth.

Given these general considerations, it can be asked whether organic chemical evolution proceeded on that planet in its early history along lines similar to those presumed to have taken place on the Earth. What isotopic, molecular, morphological, and environmental evidence for chemical evolution and the origin of life can be found on Mars?

Missions to Mars, coupled with theoretical studies, will be needed to reconstruct the history of liquid water and its interactions with surface materials, and to model the early geochemical cycles of carbon, nitrogen, sulphur, and iron. Missions are also needed, along with laboratory and theoretical model studies, to elucidate photochemical and weathering processes on Mars and the nature of inorganic carbon, nitrogen, and iron-bearing phases in the Martian surface materials. The nature of the oxidant revealed by the Viking experiments also needs to be determined, and further searches for organic compounds need to be made if we are to understand the course of chemical evolution on Mars.

It is also important to note, in connection with issues relating to the evolution of cellular and multicellular forms of life, that one aspect of the exploration of Mars is that it affords us, in principle, an opportunity to determine whether any fundamental inferences about the earliest stages of biological evolution on the Earth can be extended to Mars. That is, can we generalize our understanding about early cellular evolution on Earth by comparative studies of Mars?

In the near term, investigations into this area of research will require both *in situ* and sample return missions to Mars. Ultimately, field studies on that planet will almost certainly be necessary to maximize the opportunities for evaluating the early environment and the potential for cellular evolution on Mars.

Life Outside the Solar System

Finally, this discussion cannot be complete without some reference to the subjects of chemical evolution and the origin of life on planets *outside* our solar system.

Clearly, all of our theories ascribing the origin of life to the gradual evolution of replicating molecules as part of the process of *planetary* evolution coupled with the growing conviction that other planetary systems can be spawned in the universe, lead to the presumptive conclusion that living systems will have arisen elsewhere. To the exobiologists this possibility is considered to be quite plausible, since it represents a logical extension of our basic contentions. For this reason research directed toward finding and characterizing other planetary systems is of special significance.

Conclusion

In the foregoing brief review, an attempt has been made to describe the scope of scientific areas that comprise the current field of exobiology in the United States. From investigations of astrophysical phenomena that deal with the birth of stars and plan-

etary systems to questions of molecular biology involving phylogenetic relationships among organisms, from attempts to simulate the synthesis of biological precursor molecules in the chemistry laboratory to making measurements of the organic

constituents of Titan's atmosphere, these researches all converge toward a common objective—answering a question that humans have been asking since the dawn of their existence: “Where did we come from?”

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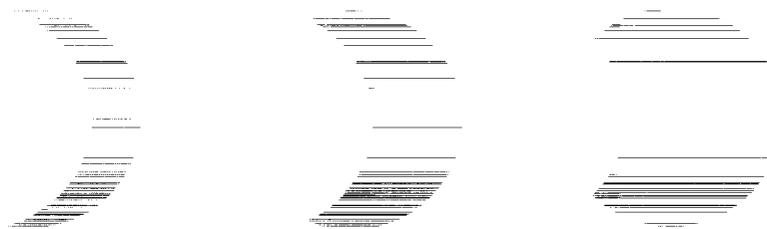
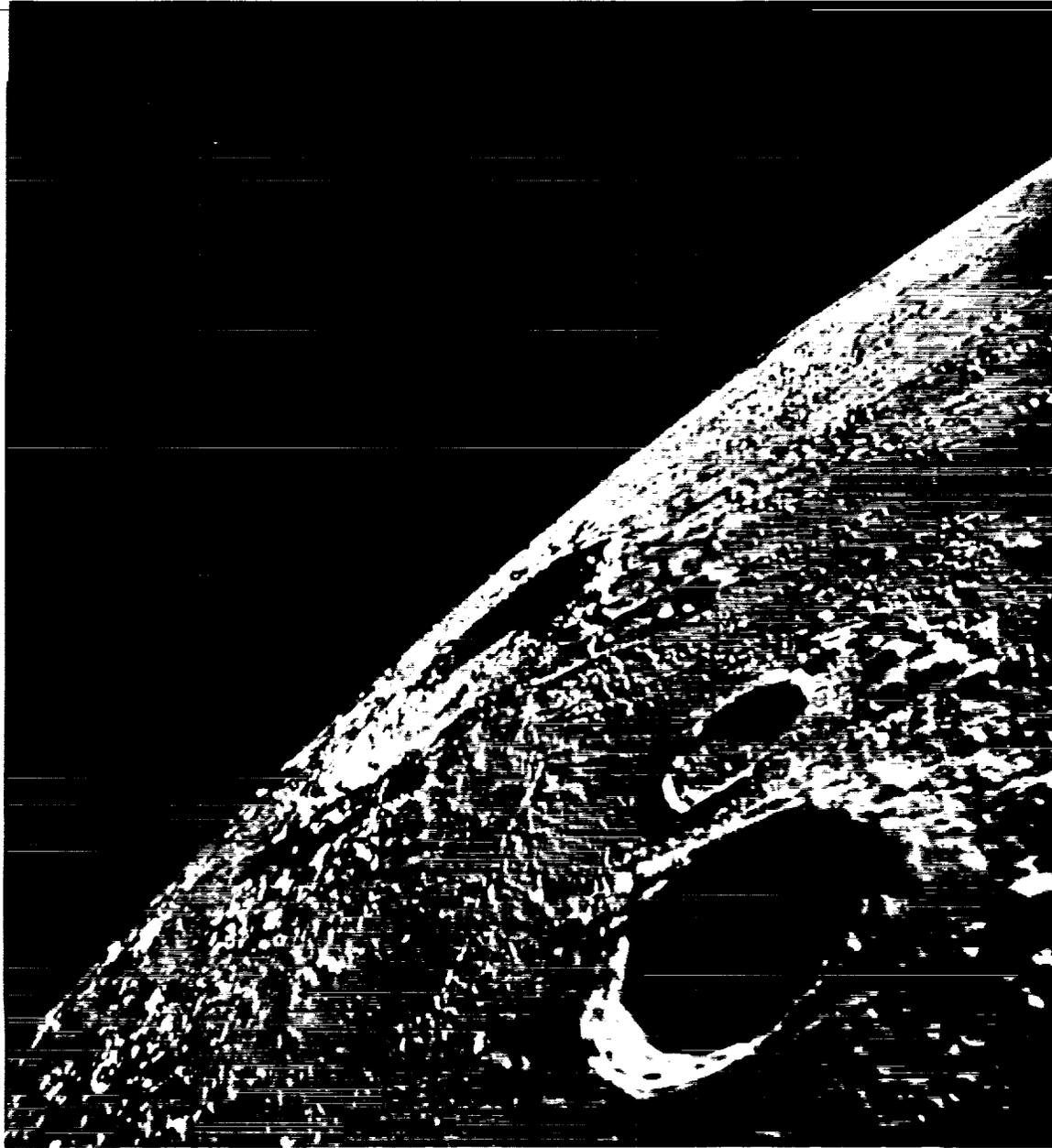
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