THE SEARCH FOR LIFE'S ORIGINS

Progress and Future Directions in Planetary Biology and Chemical Evolution

SPACE STUDIES BOARD
Committee on Planetary Biology and Chemical Evolution
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Foreword

One of the areas of interest to the Space Studies Board has long been the field of exobiology. This multidisciplinary endeavor seeks to understand the interactions between a developing and evolving biological system and the physical environments within which these evolutionary processes take place. Over the years, through its Committee on Planetary Biology and Chemical Evolution, the board has developed strategies for studies in this area, has evaluated the prospects for extant biology elsewhere in the solar system, and has provided guidelines for the protection, of both the Earth and other bodies, from the possible contamination resulting from space missions (*Post-Viking Biological Investigations of Mars* [1977]; *Recommendations on Quarantine Policy for Mars, Jupiter, Saturn, Uranus, Neptune, and Titan* [1978]; *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980s* [1981]).

A decade has passed since the board last evaluated the status of this field—a decade during which many exciting new observations and discoveries have been made, both in space missions and in ground-based laboratories and observatories. Among these may be cited new information from the Comet Halley, Voyager, and Infrared Astronomy Satellite missions; from field studies indicating the possible influences of extraterrestrial factors on biological evolution; and from laboratory studies on the replication of simple macromolecules. These and many other developments prompted the board to initiate a new study of planetary biology and chemical evolution in order to identify opportunities for conducting such investigations in space.

The current report is the result of deliberations that began with a summer study at Snowmass, Colorado, in August of 1986 and continued until the end of 1988. The resulting document includes discussions of the evolution

of organic compounds in the interstellar medium and solar nebula; assessment of the information regarding prebiotic conditions on the early Earth and of the fossil record of early terrestrial organisms; assessment of our understanding of the surface and subsurface of Mars with a view toward paleontological investigations of that planet; evaluation of the status of laboratory investigations on the origin and early evolution of life on Earth; and discussion of techniques to find evidence of biological activity in other solar systems.

These considerations are particularly important at this time as the nation approaches and plans for a period of increasingly vigorous scientific investigations in space—over the next decade and beyond—on solar-system missions and from orbiting observational platforms.

LOUIS J. LANZEROTTI, *Chairman*
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THE SEARCH FOR LIFE'S ORIGINS

Executive Summary

OVERVIEW

This report reviews the current state of the study of chemical evolution and planetary biology and discusses the probable future of the field, at least for the near term. To this end, the report lists the goals and objectives of future research and makes detailed, comprehensive recommendations for accomplishing them, emphasizing those issues that were inadequately discussed in earlier Space Studies Board reports.

The area of study described by the term "planetary biology and chemical evolution" is necessarily broad, incorporating a wide spectrum of disciplines from astronomy to paleobiology to comparative planetology. Despite their seemingly disparate natures, these disciplines are, in the present context, closely interrelated. The different elements of planetary biology and chemical evolution constitute an integrated whole; they can be viewed as a continuum in which the areas of study are interconnected by one overarching goal: to understand the evolution of living systems. What brings this field within the domain of the space sciences is its explicit reliance on spacecraft and space technology for the pursuit of this major goal.

Chapter 2 discusses the evolutionary history of the biogenic elements. The goal of research in this area is to understand the nature of the chemical and physical transformations of these elements, from their nucleosynthesis in stars to their ultimate incorporation into planetary bodies. Chapter 3 discusses a cardinal problem in the history of biological evolution, elucidating the processes by which materials came together on the primordial Earth to form the first living organisms. The current status of the field of biological evolution and recommended future research in that area are detailed in Chapter 4. Chapter 5 discusses the evolutionary context of the first repli-

cating system on this planet and identifies gaps in the present knowledge. In Chapter 6, the detection of extrasolar-system planets is considered from an exobiological point of view.

As this report attempts to show, research in chemical evolution and planetary biology is addressing one of the most fundamental and historically persistent questions: how did living things come to be on this planet? In effect, this report, then, assesses the status of our knowledge concerning the history of living things from prebiological epochs to the present. The recommendations in Chapter 7 delineate specific research objectives over the broad range of disciplines that constitute this field of scientific research, and Chapter 8 discusses policy issues related to these recommendations.

THE COSMIC HISTORY OF THE BIOGENIC ELEMENTS AND COMPOUNDS

From a terrestrial perspective, it is difficult to conceive of life forms in which the elements hydrogen, carbon, oxygen, nitrogen, sulfur, and phosphorus do not play a predominant role. That they do indeed play such a role throughout the universe seems highly probable because (apart from phosphorus) these are among the most abundant elements throughout the cosmos and, moreover, their chemistry is particularly well suited to the development of the complex structures and functions characteristic of living systems. Since the Sun and planets formed approximately 4.6 billion years ago in a universe whose age is perhaps 15 billion years, these "biogenic elements" have experienced a long and complex chemical history before being incorporated into terrestrial biochemistry.

Knowledge of the chemistry and physics of both interstellar clouds and the solar nebula will provide us with critical knowledge on how and from what materials the solar system formed. In addition, there is increasing evidence for the survival of interstellar molecular material within objects present in the solar system today, such as interplanetary dust particles, asteroids, meteorites, and comets.

The cosmic history of the biogenic elements and their compounds thus becomes a critical field of study for exobiologists. An overriding goal of this phase of the history of chemical evolution has been identified by the committee as *to understand the history of physical and chemical transformations undergone by the biogenic elements* and compounds from nucleosynthesis to their incorporation and subsequent modification in preplanetary bodies. This goal can be attained by fulfilling five major objectives:

- Determine the extent and evolution of molecular complexity in interstellar and circumstellar environments;
- Determine the composition, structure, and interrelationships among circumstellar, interstellar, and interplanetary dust;

- Assess the efficacy of chemical and physical processes in the solar nebula for altering preexisting materials and producing new compounds and phases containing the biogenic elements;
- Determine how the formation and evolution of primitive bodies modified the distribution, structure, and composition of preexisting compounds and solid phases containing the biogenic elements; and
- Determine the distribution, structure, and composition of presolar and nebular products in existing primitive materials in the solar system.

The research necessary to achieve this goal will require extensive interactions among investigators studying the origins of molecules that ultimately become the precursors for biology, as well as collaborative participation of the astronomical, astrophysical, and planetary science communities in planning and executing research strategies related to this goal.

EARLY PLANETARY ENVIRONMENTS: IMPLICATIONS FOR CHEMICAL EVOLUTION AND THE ORIGIN OF LIFE

A comparative study of planets is essential to an understanding of the relationship between planetary development and the origin and evolution of living systems. As a minimum, for life to arise and evolve on a planet, the presence of liquid water and a hydrological cycle operating in concert with geochemical cycles of the biogenic elements seem to be necessary. In a more general context, the organic chemistry of planetary environments is an extension of the cosmic evolution of the biogenic elements into the planetary epoch. Knowledge of the processes that produce organic matter wherever it occurs in the solar system is central to understanding chemical evolution. The committee has identified two major goals for studies of early planetary environments.

The first goal is *to understand the processes responsible for the chemical evolution of organic matter in the outer solar system.* Attainment of this goal can be achieved by the following objectives:

- Determine the origin and distribution of organic matter and disequilibrium products containing the biogenic elements in the hydrogen-rich atmospheres of the outer planets;
- Elucidate the organic chemistry and the origin of carbon oxides on Titan; and
- Characterize the organic matter on the dark surfaces of the asteroids, satellites, and planetary rings of the outer solar system.

The second goal is *to understand how the conditions for chemical evolution and the origin of life were influenced by the physical and chemical development of the terrestrial planets.* This goal can be attained through the following objectives:

- Determine when and how the volatile elements necessary for life were added to the surface regions of the Earth;
- Constrain the conditions on the early Earth for determining the timing and probable environments for the origin and maintenance of the first organisms; and
- Assess the isotopic, molecular, morphological, and environmental evidence for chemical evolution and the origin of life on Mars.

THE ORIGIN OF LIFE

What sparked the origin of life on the early Earth? Sources of information that may shed light on this question are the record of the early solar system as preserved in comets, asteroids, the Moon, and Mars; the geological record; the paleogeological record of ancient microorganisms and their physiological activity; and the history recorded in nucleotide and amino acid sequences found in living cells (molecular phylogeny). Stromatolitic formations in Western Australia and South Africa, at 3.5 billion years old, contain the earliest solid evidence of life on Earth, but scientists are looking for even earlier signs of life.

The study of the origin of life on Earth, a highly interdisciplinary endeavor, can be pursued in the field and in the laboratory by using two approaches: laboratory simulations and examination of the natural records of early solar-system events. The following are examples of the two approaches:

- Model systems for synthesizing fundamental biochemical monomers, to deduce the composition of Earth's early atmosphere;
- Comparative molecular biology, to deduce the characteristics of early cells by studying contemporary organisms;
- Models for replication;
- Models for the origin of gene expression; and
- Comparative planetology—studying the Moon, Venus, and Mars to help reconstruct the early history of Earth.

The committee has identified four goals to be pursued in studying the origin of life. The first is *to understand the origin and evolution of metabolism in primitive life forms.* This goal can be fulfilled by working toward the following objectives:

- Reexamination of the prebiotic origin of biomolecules in environments suggested as probable on the primitive Earth;
- Exploration of mechanisms for sequestering biomolecules on a surface or within vesicles—studies should lead to plausible prebiotic mecha-

nisms for the synthesis of molecules that could have formed vesicles, an important step toward understanding the origin of cellular metabolism;

- Identification and characterization of chemical systems capable of coenzyme functions in a prebiotic context; and
- Investigation of the nature of the earliest type of cellular metabolism.

The second goal is *to understand the origin and evolution of replication, the process that is the essence of life.* This goal can be fulfilled by working toward the following objectives:

- A search for simple organic replicating systems—template-directed replication using ribonucleotides is the most straightforward general model of replication, but even simpler systems warrant experimental study;
- Investigation of the possible role of ribonucleic acid (RNA) catalysis in replication—the isolation, sequencing, and study of small RNAs from the widest possible diversity of cells may provide new insights into the fundamental role of RNA in replication; and
- Determination of the mechanism of clay formation in nature and in the laboratory, and the possible relevance of clay to replication—the mineral theory of the origin of life postulates the existence of clay particles that have surface structures able to catalyze the organic reactions necessary to initiate organic life, and that can replicate as well.

The third goal is *to understand the origin and evolution of gene expression.* The complex system of ribosomes, transfer RNAs, and aminoacyl-transfer RNA synthetases has proven difficult to model. Comparative molecular studies of existing systems will be necessary to gain insight into the essential workings of this translation process and of the genetic code. This goal can be fulfilled by working toward the following objectives:

- Determination of the origin of codon assignments;
- Understanding the molecular mechanics of translation; and
- Phylogenetic-comparative dissection of the translation apparatus.

The fourth goal is *to determine evolutionary events leading to the accretion of complex genomes.* This goal may be fulfilled by working toward the following objective:

- Elucidation of the organization and interrelationships of phylogenetically diverse genomes.

It is clear that a major commitment for genome analysis will require support from many federal agencies besides the National Aeronautics and Space Administration (NASA); however, important aspects of this undertaking are within the purview of NASA's Exobiology Program.

THE EVOLUTION OF CELLULAR AND MULTICELLULAR LIFE

From an exobiological perspective, biological evolution is a cosmic phenomenon born of galactic and solar-system processes and influencing the development of planetary surfaces. Increasing evidence supports the concept of life intimately linked with the planet through biogeochemical cycles. The origins and evolution of life on Earth have been influenced strongly by events in the evolution of the physical Earth and also by extraterrestrial phenomena such as meteoritic bombardments. For example. recent theoretical calculations indicate that a giant impact on Earth with a Mars-sized object could have been responsible for the origin of the Moon and removal of the early Earth atmosphere. The effect of such an event on the origin of life on Earth (and elsewhere) is unclear but probably depends on the timing of the impact, the composition of the early atmosphere, and the composition of the secondary atmosphere that subsequently evolved.

A more integrated understanding of Earth's biological and physical history is necessary to understand the evolution of terrestrial life. As biological systems on Earth became more complex, they exerted greater influence on both their own development and that of the planet. The transition from physical to biological evolution of organic matter is expected to characterize all planets whose early physical evolution is comparable to Earth's.

Recent data support the view that all extant organisms on Earth descended from a common ancestor, with the three principal lines of evolutionary descent being the archaebacteria, eubacteria, and eukaryotes. All living organisms contain an extensive record of their own phylogenetic history, and molecular phylogeny should provide insight into much of this history.

The committee has identified four goals for future research on the evolution of life, all appropriate for NASA sponsorship; NASA can play a critical role in coordinating and catalyzing the necessary interdisciplinary research. The first goal is *to develop a universal understanding of the temporal sequence and evolutionary relationships of life on Earth.* This goal may be fulfilled by studying a wide variety of organisms with the techniques of molecular phylogeny and biochemical and morphological characterization.

The second goal is *to determine the properties of the universal ancestor of extant organisms.* This goal may be fulfilled by rooting the universal phylogenetic "tree." Studies of molecular phylogeny have brought this tree within reach; besides providing the starting point for studying the course of biological evolution within the three primary kingdoms, this set of phylogenetic relationships provides a framework for investigating life's history prior to the segregation of the three extant lineages. A principal objective of this line of research should be the recognition and evolutionary evaluation of gene families.

The third goal is *to understand what factors drive the biosphere.* Biological evolution has been affected by Earth's cosmic environment, and molecular phylogeny suggests that evolution proceeded in bursts. Biological, tectonic, and environmental changes appear to be closely interrelated. This goal may be fulfilled by integrating the biological accounting of the Earth's historical development with that obtained from studies of geological records and determining the influence of Earth's cosmic environment on evolution.

The fourth goal is *to generalize our understanding of environmental and early cellular evolution on Earth by comparative studies of Mars.* This goal may be fulfilled by investigating the sedimentary record of Mars for signs of biogeochemical activity.

SEARCH FOR LIFE OUTSIDE THE SOLAR SYSTEM

Life as we know it is a planetary phenomenon, requiring interactions among liquid water, gaseous atmosphere, minerals provided by the planetary surface, energy from the Sun, cosmic radiation, volcanic activity, and other sources. The oxygen-rich nonequilibrium chemistry of our atmosphere and electromagnetic radiation "leaking" from our planet are signs that life exists on Earth. As an example, the detection of such phenomena could be a key strategy in the search for life on other planets.

The committee has identified the goal as follows: *to understand the nature and distribution of life in the universe.* No unambiguous evidence of extrasolar planetary systems exists, although many tantalizing clues have been found; observational verification that other planetary systems have formed around other stars should be possible in the coming decade. The search for extrasolar planets is important to achieving this goal because life on Earth is only a single example from which it is impossible to generalize. In parallel with the search for passive evidence of life beyond our solar system, the search for evidence of technologically advanced civilizations should proceed. NASA is the leading agency in the development of most, if not all, of the detection instrumentation required for both types of searches.

To fulfill the goal of understanding the nature of the distribution of life in the universe, the committee recommends pursuing the following objectives:

- Determination of the frequency and morphology of nearby planetary systems—this will require a new generation of instruments capable of detecting low-mass planets and investigating solar-system-scale phenomena within protoplanetary disks in nearby regions of star formation;
- Determination of the frequency of occurrence of conditions suitable to the origin of life—obtaining information on the surface temperature and atmospheric chemical composition of extrasolar planets requires direct im-

aging and spectroscopic analyses, and the technology required for such observations is not yet available;

- Search for presumptive evidence of life in other planetary systems; and
- Search for evidence of extraterrestrial technology.

MAJOR RESEARCH RECOMMENDATIONS

The recommendations in Chapter 7 fall into two general categories: those that require observations and experiments to be conducted on either planetary missions or facilities in Earth orbit, and those that include observations, experiments, and theoretical modeling studies that can be carried out in ground-based facilities. In view of the generally large differences in cost and complexity between these two categories, the committee assigns priorities within the two groups separately. Within each group, lists have been priority ordered on the basis of a combination of near-term feasibility and scientific importance.

Recommendations Requiring Flight Opportunities

Mars

The highest priority in the category requiring flight missions is accorded to studies of Mars. It is hard to imagine more exciting and fundamental questions than those concerning the early surficial environment and the possibility of chemical or even biological evolution on the early surface of our neighboring planet. Furthermore, Mars is the only other object in the solar system on which an earlier origin of life could have left a well-preserved, exposed record. Sedimentary rocks on Mars may contain a record of the interval in chemical evolution that is nowhere preserved on the Earth and may thus contribute to understanding the processes that led to the origin and early evolution of organisms on this planet. Thus, investigations of Mars can contribute to the elucidation of objectives discussed previously in connection with early planetary environments and the origin of life—both on the Earth and, possibly, on Mars—as well as with the course of biological evolution on this planet. The committee therefore recommends studies to

- Conduct chemical, isotopic, mineralogical, sedimentological, and paleontological studies of Martian surface materials at sites where there is evidence of hydrologic activity in any early clement epoch, through in situ determinations and through analysis of returned samples; of primary interest are sites in the channel networks and outflow plains; highest priority is assigned to sites in which there is evidence suggestive of water-lain sedi-

ments on the floors of canyons as in the Valles Marineris system, particularly Hebes and Candor chasmata; and

- Reconstruct the history of liquid water and its interactions with surface materials on Mars through photogeologic studies, space-based spectral reflectivity measurements, in situ measurements, and analysis of returned samples.

Comets and Asteroids

Critical information about the chemical nature, and early processing, of materials containing the biogenic elements (i.e., the evolution of organic complexity in the solar nebula) can be obtained from the study of these relatively unmetamorphosed materials of the solar system. Such studies can lead to an understanding of the role of these bodies in supplying the primitive Earth with the organic constituents and volatiles necessary for the origin of life on the planet. Furthermore, these bodies are also of interest as projectiles that may have had significant effects on the course of biological evolution by impacting the Earth. The committee therefore recommends that

- Measurements be made, by remote spectroscopic observations and in situ, of the elemental and isotopic composition of cometary comae and nuclei and of the principal asteroid types, including determination of the molecular composition of components containing the biogenic elements hydrogen, carbon, nitrogen, oxygen, phosphorus, and sulfur in comets and primitive asteroids; such measurements should be made at various surface locations and depths to determine the degree of homogeneity; and
- A cometary sample be obtained for detailed laboratory analysis of atmospheric, surface, and subsurface materials.

Titan and the Giant Outer Planets

The outer planets, in contrast to the inner, represent bodies with atmospheres dominated by hydrogen and containing organic constituents. Study of these objects can yield considerable insight about the processes involved in the formation of organic compounds under natural conditions in a hydrogen-rich environment. Much interesting chemistry must also be taking place in the strongly reducing atmosphere of Titan. Thus, investigations of these objects can be expected to shed much light on one model for the formation of life on the Earth, in which a reducing atmosphere has been invoked. The committee therefore recommends studies to

- Identify the compositions, and measure the abundances and distributions, of gaseous organic compounds and organic haze particles in Titan's

atmosphere by using atmospheric entry probes and remote astronomical observations.

- Elucidate the distribution, with altitude, of organic matter, carbon monoxide, and phosphine in the atmospheres of Jupiter and Saturn by using atmospheric entry probe measurements and astronomical observations.

The Interstellar Medium and Cosmic Dust Particles

The earliest stages of chemical processing involving the biogenic elements are taking place in molecular clouds and protosolar nebulae. Studies of these objects can therefore answer fundamental questions about the early history of organic chemical evolution. For investigation of the interstellar and protostellar regions, significant advances in our understanding of early organic chemical evolution can be realized by opening up those portions of the infrared- through millimeter-wavelength spectrum for which the atmosphere is opaque. Additional opportunities to increase understanding of processes and events in the evolution of volatiles and organic materials in the early solar system can be attained by the study of extraterrestrial dust particles. For effective probing of these scientific issues, the committee

- Strongly supports the development of high spectral resolution, Earth-orbital facilities for astronomical observations at infrared, submillimeter, and millimeter wavelengths; and
- Recommends Earth-orbital collection of interplanetary (and potentially interstellar) dust particles—including, ultimately, nondestructive methods of collection—to allow their detailed chemical and isotopic analysis.

Recommendations Requiring Ground-Based Studies

Chemical Evolution and the Origin of Life

Scientific developments over the past decade that bear on the processes leading to the origin of life have resulted in an expansion in emphasis from prebiotic chemistry into biochemical evolution as well. One consequence of this expansion is that work of high interest to the exobiology community, and supported by NASA, has increasingly come to overlap studies supported by other federal agencies such as the National Institutes of Health (NIH) and the National Science Foundation (NSF). NASA's continuing support is critical, however, because only it provides the programmatic integration that promotes the necessary cross-fertilization of the various disciplines relevant to exobiology. As in the past, NASA programs in this field should strive to avoid duplicating the efforts of other agencies and should complement the work of these agencies by focusing on issues that

directly concern interactions between the physical and chemical environments that led to the development and evolution of organisms on this planet. Accordingly, the committee recommends

- The reexamination of biological monomer synthesis under primitive Earth-like environments, as revealed in current models of the early Earth, and the synthesis and study of simple model systems for fundamental biological processes such as polynucleotide replication, sequestration of biomolecules, coenzyme functions, and elements of the translation system in protein syntheses;
- The development of improved data on the biological and physical development of the Earth by modeling the geochemistry of the prebiotic and earliest biotic oceans to obtain their composition and their physical and chemical responses to large impacts, and by careful sedimentological, geochemical, and paleontological analysis of ancient sedimentary basins; local environments favorable to the origin of life should be identified and characterized geophysically and geochemically: geological research should be aimed not only at the elucidation of environmental evolution but also at understanding the cosmic influences on terrestrial environments and evolution;
- Studies designed to recognize extraterrestrial signatures in sedimentary successions and research to evaluate temporal patterns in the composition of the biota (as recorded in the fossil record) in light of recognizable extraterrestrial signals;
- The continued search on Earth for igneous and sedimentary rocks formed prior to 3.8 billion years ago; and
- The development of robust phylogenies relating living organisms, through the comparison of sequences in informational macromolecules, especially small subunit ribosomal RNAs, and the elucidation of the biochemical and ultrastructural characters of microorganisms in order to relate patterns of phenotypic diversity to phylogeny.

Mars-Related Studies

Ground-based studies are necessary to understand present environmental conditions in order to plan effective exploratory investigations related to exobiology. The committee therefore recommends that

- Laboratory and theoretical model studies be carried out of photochemical and weathering processes on Mars that will determine the nature of inorganic carbon, nitrogen, sulfur, and iron-bearing phases in Martian surface soils, will indicate the geochemical cycles of these elements during an earlier aqueous epoch, and will characterize the nature of the oxidants revealed by the Viking experiments; and
- Scenarios be developed for chemical evolution and the origin of life

on Mars, based on our knowledge of these processes on Earth, but bounded by existing data and theory on the accretionary, tectonic, geologic, and climatic history of Mars.

Studies Related to Comets and Asteroids

These bodies of the solar system are of interest to the field of exobiology from many points of view: as projectiles impacting the planets, as possible sources for the biogenic elements and volatiles on the terrestrial planets, and as reservoirs of information about the early history of the solar system. In relation to these issues, the committee recommends

- The maintenance of a vigorous program of research on the chemical, isotopic, mineralogical, and petrographic properties of meteorites and laboratory studies of the molecular and isotopic compositions and yields of organic molecules produced in realistic simulations of those astrophysical environments within which presolar constituents of carbonaceous meteorites may have been produced; and
- Theoretical studies on the physics of comet formation, to determine the maximum size of comets accreted in the solar nebula, as well as thermocalculations of the composition of atmospheres produced by large impacts of cometary and various asteroidal-type bodies.

Studies Related to Titan and the Giant Outer Planets

Theoretical modeling and laboratory studies are required to elucidate the organic chemistry in the atmospheres of Titan and the giant planets, as well as to effectively interpret relevant data obtained from missions to these objects. The committee therefore recommends that

- Simulations be carried out of organic synthesis resulting from the deposition of electrons, photons, and cosmic rays into Titan's atmosphere and that similar experiments, as well as computer simulations, be conducted that will yield predictions of the molecular compositions and abundances of organic matter produced by processes operating at various levels in the atmospheres of Jupiter and Saturn.

Studies Related to the Interstellar Medium and Dust

Data from laboratory investigations and from theoretical modeling are necessary to prepare for, understand, and extend the results obtained from space-borne experiments aimed at studying the interstellar medium and dust

particles of interstellar and interplanetary origin. For these purposes, the committee recommends

- Study of the spectra of, and chemical processes involving, potential gas and grain constituents of molecular clouds that are the sites of star and planetary formations, as well as study of gas and grain reactions under conditions consistent with realistic models of the solar nebula, including a variety of nonequilibrium processes, and of the growth and destruction of grain aggregates;
- Utilization of ground-based telescopic facilities to probe the chemistry and physics of star-forming regions in detail, and development of the instrumentation necessary to maximize the scientific return from space-based, laboratory, and telescopic measurements, including broad-bandwidth, high-resolution spectrometers, and microanalytical techniques;
- Maintaining a vigorous program of research on the chemical and isotopic properties of dust particles of extraterrestrial origins; and
- Theoretical modeling of chemical and physical processes, including grain growth, in the solar nebula and in interstellar, circumstellar, and protostellar environments.

Studies Related to the Search for Life Outside the Solar System

Two parallel avenues of research should be pursued in attempts to detect life beyond the solar system: searches for evidence of biological modification of an extrasolar planet and searches for evidence of extraterrestrial technology. These separate approaches can conceivably influence each other. For example, if a nearby solar-type star is found to have a planetary system, it would become a prime target in the search for extraterrestrial intelligence (SETI); similarly, if a "SETI signal" were detected from the direction of some nearby star, intensive efforts would undoubtedly be made to image and study the host planet. Because both lines of investigation proceed simultaneously, the overall priorities listed below are those suggested naturally by the existing maturity of the requisite instrumentation. For these studies, the committee recommends

- Continued support for ground-based and earth-orbital searches for extrasolar planets;
- Commencement of a systematic ground-based search through the low end of the microwave window for evidence of signals from an extraterrestrial technology; and
- Studies leading to the development of future technologies for these investigations, including large-scale optical, infrared, and submillimeter arrays or monoliths in orbit or on lunar farside for imaging extrasolar planets

and protoplanetary nebulae; a dedicated SETI facility with radio frequency interference (RFI) protection in high Earth orbit or on lunar farside; advanced data-processing techniques; and substantive original or unconventional approaches to the detection of other technological civilizations.

SPACE SCIENCE PROGRAM AND POLICY ISSUES

Research in planetary biology and chemical evolution extends over many "classical" scientific disciplines and brings together investigators from seemingly disparate areas.

Over the last two decades, this field has developed to the point at which evolutionary themes on cosmological, chemical, and biological levels have become major foundations from which studies are undertaken. With these common evolutionary themes and the exposition of continuous cause and effect between evolving biological and planetary systems, communication across scientific disciplines has become at least as important as that within the disciplines themselves. Maintenance of this broad "mix" of biological and physical sciences, and of ground- and space-based investigations, is unique to the space sciences and critical to the effective conduct of a vigorous national program in chemical evolution and planetary biology.

The current efforts of NASA in chemical evolution and planetary biology are administered almost entirely by the Exobiology Program Office within the Life Sciences Division of the agency. On the other hand, planning for, and implementation of, space missions not directly concerned with space medicine or space biology are conducted by other divisions of NASA. Although consideration has often been given to exobiology objectives in the development of mission plans, much stronger interaction is needed between mission planners and the exobiology science community. To enhance the utility of future missions for those areas of inquiry that are the subject of this report, the advice of qualified scientists should be utilized in the planning and implementation of these missions.

The committee also urges NASA to encourage the timely development of instrumentation for potential use in space experiments involving planetary biology and chemical evolution, well in advance of payload selection, by setting aside specific funds for this purpose.

Because of the essential role of space technology in many aspects of research in planetary biology and chemical evolution, almost all of the support for this field, and for integration of its various elements, is now borne by a single federal agency, NASA, through its grants and in-house activities. Nevertheless, other federal agencies, notably the NSF and NIH, support research that may be directly related to the overall goals of this program. NASA should explore mechanisms for closer interaction with its sister agencies in order to maximize national efforts, especially in areas that

might be jointly funded. Such interactions can serve to inform a much wider circle of scientists than might otherwise be reached, of the goals, objectives, and opportunities of the NASA programs in chemical evolution and planetary biology and, at the same time, could bring new ideas and fresh approaches into the field.

In this regard, the committee is conscious of the fact that potentially interested scientists are often unaware of NASA's goals in this area. NASA should devise ways to reach more broadly into the scientific community by delineating and publicizing its goals and objectives and also by establishing more clearly the procedures through which entry can be made into the program.

It is also important for NASA to educate the scientific community about the many areas of evolutionary biology in which data obtained from space missions have enhanced understanding of the course of evolution. NASA should make a greater effort to bring to the attention of the scientific community the potential benefits to be derived from the use of space technology.

Because of the interdisciplinary nature of this field, there is an obvious need for frequent and sustained cross communication among the various disciplines that contribute to the overall goals of the program. To implement this need, NASA should establish procedures that will encourage more effective communication among molecular/evolutionary/biospheric biologists, paleontologists, astronomers, geologists, and planetary modelers both from within NASA centers and from the academic community. Opportunities for such interactions can be facilitated by NASA sponsorship of workshops, symposia, and innovative interdisciplinary research projects.

Also, because the subject matter of this field cuts across both the physical and the biological sciences, specific training in this area is not normally available to students as they prepare for their scientific careers, and young people entering into the pool of scientific talent are less apt to seek careers in chemical evolution and planetary biology. To surmount this deficiency, NASA should develop a program of specific postdoctoral fellowships in the field by which candidates would be able to pursue advanced studies either at NASA in-house laboratories or with university specialists.

1

Overview

In the 1970s, the major focus of the Committee on Planetary Biology and Chemical Evolution of the Space Studies Board (SSB) centered on the planet Mars. Initially, attention was directed at assessing the prospects for finding extant organisms on that planet and developing guidelines for the biological containment both of terrestrial materials that might be transported to Mars and of Martian material that might be returned to Earth. Later, as data from the Viking spacecraft and from ground-based simulations of the Viking biological experiments were made available, the committee became involved in the analysis and interpretation of the Viking Mars biological data.

In the past decade, the scientific thrust of the committee shifted substantially from solar-system exploration to studies of the Earth with the publication of two documents. The first of these, *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980s* (SSB, 1981), while discussing the state of knowledge in the field of planetary biology and chemical evolution, proposed as its main recommendation the development of an integrated new program to study the global interactions between terrestrial organisms and this planet. More recently, this theme was further elaborated with the publication of *Remote Sensing of the Biosphere* (SSB, 1986a). Other recent reports of the Space Studies Board that relate to this field are *A Strategy for Earth Science from Space in the 1980s,* Part I (SSB, 1982) and *A Strategy for Earth Science from Space in the 1980s and 1990s,* Part II (SSB, 1985).

Superficially, it might appear that the search for life on Mars and studies of the Earth's biosphere are remotely related areas of scientific inquiry. In fact, both avenues of study have, as their basis, a desire to gain an understanding of the processes involved in the development and maintenance of a biota on a planet, which requires insight into the interactions between an

evolving biological system and its planetary environment. Thus the overall theme of studies on chemical evolution and planetary biology is one of evolution.

A considerable amount of new information and new methodology has accrued since publication of these earlier reports. The purpose of the present report is to review the current state of this field, which has expanded into several new areas of inquiry. This report indicates objectives of future research in the various aspects of planetary biology and chemical evolution and makes detailed and comprehensive recommendations for accomplishing them. Issues that were inadequately discussed in earlier reports are emphasized here, and issues that have been treated in detail before are omitted. For example, this report does not consider current interactions between the Earth and its biota, because detailed attention was given to various aspects of this issue in the 1986 SSB study.

As can be seen in the following chapters, the subject matter of this field—which is generally referred to as "exobiology"—involves a very wide spectrum of disciplines from astronomy to paleobiology. Some of the research described requires direct analysis of solar-system objects through the use of spacecraft; other areas utilize both ground-based and space-borne observational techniques to probe the solar system and beyond; and still other lines of investigation are to be carried out in the field and in terrestrial laboratories. Despite their seemingly disparate natures, the different elements of planetary biology and chemical evolution constitute an integrated whole. They can be viewed as a continuum in which the areas of study are bound together by one underlying goal: *to understand the evolution of living systems*. In addition, what makes this field the domain of the space sciences is its explicit reliance on spacecraft and space technology for implementation of this major goal.

This report, then, assesses the status of our knowledge concerning the history of living things from prebiological epochs to the present. As such, the field extends backward in time to when the elements necessary for life (the so-called biogenic elements) were incorporated into the organic components of the gases and grains of the interstellar medium from which our solar nebula was formed, and it attempts to trace the history of these materials. Chapter 2 discusses the area of chemical evolution, whose goal is to understand the nature of the chemical and physical transformations of the biogenic elements—from their nucleosynthesis to their ultimate incorporation into planetary bodies. To achieve this understanding requires information from diverse sources, involving not only ground-based observations and laboratory studies but also space-borne observations and analyses of objects such as comets, asteroids, other solar-system bodies, and different stellar and protostellar systems. In addition, investigators studying the origins of the molecules that ultimately become the precursors for biology

must interact with the astronomical, astrophysical, and planetary science communities and participate with them in the planning and execution of relevant programs.

Chapter 3 discusses a cardinal problem in the history of biological evolution, namely, elucidating the processes by which materials came together on the primordial Earth to form the first living organisms. Were the biogenic elements and organic molecules on the newly accreted Earth already present and adequate for the subsequent emergence of life? What, if any, were the contributions of comets, meteorites, and cosmic dust? What was the environmental "envelope" on this planet that permitted, first, the emergence of life and, then, its subsequent maintenance? For answers to these questions, the geological record on Earth for this period of its history is essentially unavailable, owing, in part, to weathering and to tectonic and volcanic activity. Indeed, the cumulative effects of billions of years of metabolic activity on the part of the Earth's biota itself have also contributed to the erasure of earlier records of the Earth's history. However, records do go back to this epoch elsewhere in the solar system. Portions of the surfaces of the Moon and Mars apparently have survived since the formation of the solar system and are, in principle, available for detailed analyses. The outer planets and their satellites, as well as comets and asteroids, hold additional clues on the nature of the primordial solar nebula from which the Earth was formed. It should be apparent, therefore, that one very important source of data with which to model the environment of the Earth during the period when life was emerging is the knowledge gained from intensive exploration of the solar system.

Laboratory studies aimed at finding mechanisms to explain the specific chemical processes that produced replicating molecules on Earth constitute an integral and essential part of the research activity involved in deciphering the course of chemical evolution. The current status of this area of research and recommended future studies are detailed in Chapter 4. Since the pioneering experiments of S. Miller and H. Urey in the early 1950s, great strides have been made in elucidating plausible reactions by which most of the biologically important monomers could have been produced on the prebiotic Earth. Many of these processes were discussed in the 1981 SSB document. However, new insights have been obtained in more recent years in a number of areas relevant to studies on the origin of life. These include the demonstration of routes by which polymerization of nucleic acid monomers may have occurred on the primitive Earth, new ideas about the possible role of RNA as a self-replicating molecule, and new theories about the possible role of clays. All of these require further intensive investigation and indicate that fresh approaches to research on the origin of life are in order.

When the first replicating system appeared on this planet is unknown at

present, although it probably occurred early in our planet's history. Sedimentary rocks deposited 3.5 billion years ago contain paleontological and geochemical evidence that microbial communities were already well established at that time. Could the origin of life have occurred soon after the Earth was formed, that is, during the postaccretionary period when large objects were impacting the Earth? What would have been the effects of these large impacting bodies on the stability of the Earth's biota? Some insight into these questions has already been obtained from studies of the impact basins on the Moon, because much of its early record still remains. However, more comprehensive studies of impact craters on the Moon, Mars, and other solar-system bodies aimed at characterizing the size and velocity of the impacting bodies are required to understand how these large projectiles may have influenced early life on Earth. Scientists interested in chemical evolution and planetary biology clearly must interact with geologists and geophysicists in these studies, and their interests must be represented in the planning of lunar planetary missions.

As discussed in Chapter 5, the nature of the first replicating system on this planet is also unknown. The fossil record, which goes back 3.5 billion years, provides only general clues concerning the properties of the organisms of that period. Moreover, the nature of the organisms that must have existed even earlier can be constrained in only a general way by this evidence. To address this problem, a powerful new approach has come into extensive use in the past decade. This involves techniques of comparative molecular biology, in which large molecules, particularly nucleic acids, from diverse organisms are sequenced in order to compare their relatedness. From such determinations, evolutionary "trees" can be deduced, and the sequence of appearance of different types of organisms can be inferred. From this line of investigation, it has been possible to trace evolutionary lineages back to very early points in the course of biological evolution, when different kinds of organisms diverged from each other. Further research along these lines may enable a characterization of the so-called universal ancestor of all extant organisms. In this regard, any meaningful inferences about the nature of this ancestor must be made within the context of reasonable models of the terrestrial environment of that period. As a corollary, studying the phylogeny of organisms can also lead to inferences about the environment of the early Earth.

Deducing the early environmental history of the Earth, although largely the province of geologists and planetary modelers is thus of great importance to biologists interested in early evolution. Indeed, evolutionary biologists are becoming increasingly aware that the course of biological evolution, over its entire history, simply cannot be viewed as operating independently of planetary conditions. Variations in the Earth's climate due to orbital perturbations, changes in solar luminosity, and impacts of comets or

asteroids on the Earth are among the extrinsic factors recently proposed by evolutionary scientists as agents that could substantially modify the Earth's climate, with resulting changes in the direction and pace of evolution of terrestrial biota. This new view of the potential role of extraterrestrial events portends increased interdisciplinary activity on the part of the biological and space science communities. The interplay between these sciences is creating a synergism of benefit to both. For example, paleobiological data indicating periodicity in mass extinctions of terrestrial organisms have stimulated inquiry into possible periodic astronomical phenomena and their effects on the environment.

The intellectual content of chemical evolution and planetary biology cannot be complete without a consideration of whether the processes thought to have led to the origin and evolution of terrestrial life also occurred on other bodies in the universe. Recent astronomical observations suggesting the formation of planetary systems around other stars point to the very real potential for discovering extrasolar-system planets in the not-too-distant future. In an upcoming SSB study, *A Strategy for the Detection and Study of Extrasolar Planetary Materials: 1990–2000* (in press), the current status of this field is reviewed and techniques to implement a search for other planetary systems are discussed. In Chapter 6 of the present report, the detection of extrasolar-system planets is also considered, but the focus is on whether other planets exist that have undergone chemical evolution to the point of producing living systems and on techniques that might be used to determine the presence of organisms on such bodies.

As this report attempts to show, research in chemical evolution and planetary biology is addressing one of the most fundamental and historically persistent questions humans have asked: how did living things come to be on this planet? A broad outline of the processes by which primordial matter, derived from ancient lineages of stars, ultimately was transformed into living organisms is reasonably well understood. However, many of the details and, more important, many of the key questions involved remain for future study and discovery. Only an interdisciplinary attack, pursued along many different lines of research, is likely to resolve the major issues. The recommendations in the ensuing chapters delineate specific research objectives over the broad range of disciplines that constitute this field.

2

The Cosmic History of the Biogenic Elements and Compounds

INTRODUCTION

From our terrestrial perspective it is difficult to conceive of life forms in which the elements hydrogen, carbon, oxygen, nitrogen, sulfur, and phosphorus do not play a predominant role. That they do indeed play such a role throughout the universe seems highly probable, in part because (apart from phosphorus) these are the most abundant elements throughout the cosmos and they occur in significant quantities among the building blocks of terrestrial planets as represented by the primitive chondrites and comets. Moreover, their chemistry is particularly well suited to the development of the complex structures and functions characteristic of living systems. Since the Sun and planets formed only some 4.6 billion years ago in a universe whose age is perhaps 15 billion years, it is clear that these "biogenic elements" experienced a long and complex chemical history before being incorporated into terrestrial biochemistry. At present it is not known whether this prior history played a direct role in the origin of life on Earth. What is clear is that astrochemistry is to a large extent the chemistry of the biogenic elements and that understanding the nature and evolution of chemical complexity throughout the universe is crucial to understanding both the early chemical state of our own solar system and the frequency with which similar or related conditions exist elsewhere in our galaxy and other galaxies.

There is, in addition, increasingly suggestive evidence for the survival of interstellar molecular material within objects present in the solar system today. Such evidence comes from studies of the isotopic compositions of the carbonaceous components of certain meteorites and from the inferred chemical composition of cometary nuclei, the latter supported by models derived from recent spacecraft encounters. Moreover, some current models

of the solar nebula suggest that the bulk of the Earth's volatiles would not have condensed at 1 AU from the Sun, implying that they were provided by a bombardment of the Earth by volatile-rich cometary and meteoroidal debris, which may well have contained interstellar components.

At the least, these ideas imply links between the chemistry of primitive objects in the solar system and the interstellar environment in which the Sun and planets formed and that such links involve the chemistry of the elements necessary for the origin of life on Earth. Certainly, a knowledge of the chemistry and physics of both interstellar clouds and the solar nebula will provide crucial information on how and from what materials the solar system was formed.

The cosmic history of the biogenic elements and their compounds thus becomes a critical field of study for exobiologists. Apart from hydrogen, which is for all essential purposes primordial, these elements are formed in the interiors of stars and returned to the interstellar medium either in the violent events accompanying the late stages of evolution of a massive star (supernova explosions) or in the even larger amounts of processed material expelled continuously or episodically from stars in late stages of their life cycles. The subsequent of chemical complexity is a complicated and still poorly understood story, involving condensation of particulate material ("dust") in the outflowing envelopes around evolved stars, gas-phase reactions that build complex organic molecules in dense interstellar clouds of gas and dust, and interaction of the particulate and gaseous phases with the interstellar radiation field and cosmic rays.

In circumstellar and interstellar regions, astronomers have unequivocally identified gaseous organic molecules with up to 13 atoms and molecular weights twice that of glycine, the simplest amino acid. Although the presence of an interstellar "dust" component has been known for more than 50 years, its composition, structure, and spacial variations are still subjects of heated controversy. Evidence is accumulating, however, that the size of these dust particles may well overlap that of large molecules, and their composition, in terms of biogenic compounds, quite likely ranges from water and amorphous carbon or graphite to complex, heterocyclic organic polymers.

It is within the denser interstellar clouds that new stars and planetary systems form. The details of this process are not well understood. Nonetheless, it is generally accepted that the physical and chemical properties of the biogenic compounds play a crucial role in the thermodynamics of star formation, because radiative energy loss from these molecules allows the cloud to cool and hence to collapse. Moreover, the trace biogenic constituents provide critical probes of the physical, chemical, and kinematic states of both interstellar clouds and protostellar systems, by way of their rotational and vibrational transitions observable at radio and infrared wavelengths.

How much of this interstellar chemistry is preserved as the parent molecular cloud collapses to yield the protosun, as the accretion disk develops into the solar nebula, and as the building blocks of the planets accrete, is uncertain. The investigation of possible links between the chemistries of these stages in solar-system formation, and the determination of physical and chemical conditions during this process by studying both primitive objects and molecular clouds, are fascinating and crucial areas to be explored in coming years. It is clear that the solar nebula was not in chemical equilibrium. Can local kinetic processes mimic those that occurred under interstellar conditions? What new organic compounds might have formed in the solar nebula or on the primitive bodies of the solar system? Can the processes operating on primitive bodies give insight into chemical evolution on Earth? Detailed analysis of the chemistry and structure of compounds and phases containing the biogenic elements in surviving primitive material, including comets, can probe such questions.

The single overriding goal of this phase of evolutionary history is stated below. Five major objectives contributing to the achievement of this goal follow.

GOAL: *To understand the history of physical and chemical transformations undergone by the biogenic elements and compounds, from nucleosynthesis to their incorporation and subsequent modification in preplanetary bodies.*

OBJECTIVE 1: *To determine the extent and the evolution of molecular complexity in interstellar and circumstellar environments.*

Almost 20 years have passed since the first gaseous polyatomic molecules—ammonia (NH_3) and water (H_2O)—were discovered in the interstellar medium via the technique of radio astronomy. Since that time, more than 80 different molecular species and numerous isotopic modifications have been identified unambiguously in the gas phase. Most of these species have been detected through their rotational transition frequencies at radio wavelengths (the term "radio" is often used to apply to wavelengths of 1 mm or less), although a few molecules, especially in circumstellar sources, have been characterized by their vibrational spectra in the infrared. The detected molecules range in complexity from diatomics such as hydrogen (H_2) and carbon monoxide (CO) to a 13-atom unsaturated linear nitrile $HC_{11}N$ and include many simple organic molecules (Table 2.1). Typically, molecules involving the biogenic elements carbon, nitrogen, and oxygen are trace constituents of a gas dominated by molecular hydrogen. Nevertheless, the large mass of "dense" interstellar clouds implies that there is substantially more organic matter in a typical cloud than on the Earth. In addition to the existence of organic molecules, dense interstellar clouds have other

TABLE 2.1 Identified Interstellar Molecules

Simple Hydrides, Oxides, Sulfides, Halides, and Related Molecules				
H_2	CO	NH_3	CS	$NaCl^x$
HCl	SiO	SiH_4^x	SiS	$AlCl^x$
H_2O	SO_2	CC	H_2S	KCl^x
	OCS	CH_4^x	PN	AlF^x
	HNO (?)	SiC^x		
Nitriles, Acetylene Derivatives, and Related Molecules				
HCN	HC≡C—CN	$H_3C—C≡C—CN$	$H_3C—CH_2—CN$	$H_2C=CH_2^x$
H_3CCN	$H(C≡C)_2—CN$	$H_3C—C≡CH$	$H_2C=CH—CN$	$HC≡CH^x$
CCO(?)	$H(C≡C)_3—CN$	$H_3C—(C≡C)_2—H$	HNC	
CCCO	$H(C≡C)_4—CN$	$H_3C—(C≡C)_2—CN$?	HN=C=O	
CCCS	$H(C≡C)_5—CN$	HN=C=S		
HC≡CCHO				
H_3CNC				
Aldehydes, Alcohols, Ethers, Ketones, Amides, and Related Molecules				
$H_2C=O$	H_3COH	HO—CH=O	H_2CNH	
$H_2C=S$	$H_3C—CH_2—OH$	$H_3C—O—CH=O$	H_3CNH_2	
$H_3C—CH=O$	H_3CSH	$H_3C—O—CH_3$	H_2NCN	
$NH_2—CH=O$	$(CH_3)_2CO$ (?)	$H_2C=C=O$		
Cyclic Molecules				
C_3H_2	SiC_2	C_3H		
Ions				
CH^+	HCO^+	H_3O^+ (?)		
H_2D^+ (?)	$HOCO^+$	$HCNH^+$		
HN_2^+	HCS^+	SO^+		
	HOC^+ (?)			
Radicals				
CH	C_3H	CN	HCO	C_2S
OH	C_4H	C_3N	NO	SO
C_2H	C_5H	H_2CCN	NS	
	C_6H			

NOTE: The superscript x indicates detection only in the envelopes around evolved stars. A question mark (?) indicates molecules claimed but not yet confirmed.

features in common, such as a preponderance of gas-phase matter (with perhaps 1 percent of the material in the form of solid dust grains), temperatures well below those on Earth (10 to 100 K), gas densities quite low by terrestrial standards (10^3 to 10^6 molecules/cm^3), and chemically "reducing" environments in which H_2 is the dominant molecular species but in which oxygenated molecules also exist. The most massive objects, "giant" molecular clouds, are larger, hotter (100 K versus 10 K), and show more evidence of past and present massive star formations than the much smaller

"dark clouds." Circumstellar sources appear to exhibit a significant organic chemistry only if, unlike most objects, they are carbon- rather than oxygen-rich. In such stellar envelopes, the gas density and temperature are severe functions of the distance from the center of the star.

Although the spectra of many gaseous molecules have been detected in interstellar and circumstellar sources, most astronomers have been less interested in the chemical composition of these sources than in utilizing the spectra of abundant species such as CO and NH_3 to probe the prevailing physical conditions. High priority in the next decade should therefore be accorded to a systematic study of the chemical composition of interstellar and circumstellar clouds. Of particular interest in the context of exobiology are studies of the degree of molecular complexity that can be attained and of the diversity of chemical compositions that are produced as a result of evolutionary effects and different physical conditions.

SYSTEMATIC STUDIES OF INTERSTELLAR CLOUDS

Although much has been learned about individual interstellar and circumstellar sources, a systematic study of the gas-phase chemistry of any of these sources has not yet been achieved, even though portions of such studies are available. A systematic study would entail determination of the following: the chemical state of the major elements, including the biogenic ones; isotopic abundances and isotopic fractionation effects; the way in which abundances of major constituents vary as functions of position and physical conditions within the cloud and possible cloud history; and the extent of molecular complexity (see below).

Consider oxygen as an example of how little is known about the dominant repositories of the major elements. It is argued indirectly that oxygen (O_2) and water (H_2O) are probably the most abundant oxygen-containing species after CO in the gas phase of interstellar and circumstellar clouds, and yet it is difficult to study these species from the ground or even from aircraft because of atmospheric absorption. A strategy for determining the abundances of these important gas-phase species via their millimeter and submillimeter transitions requires space-based instrumentation, perhaps initially of the Explorer class, but ultimately employing the higher angular resolution of the proposed Large Deployable Reflector (LDR) and the Space Infrared Telescope Facility (SIRTF) spacecraft *(Space Science in the Twenty-First Century,* SSB, 1988a,c). Consider, as a second example, the case of carbon. A significant fraction of carbon abundance in the gas phase is in the form of CO. However, it is unclear how much is in the form of carbon dioxide (CO_2) or simple hydrocarbons such as methane (CH_4) and acetylene (C_2H_2), because these nonpolar species do not possess strong rotational spectra. To determine their importance, infrared techniques will have to be

utilized to observe vibrational transitions. It is clear from atmospheric absorption at these wavelengths and from the currently limited sensitivity of ground-based infrared telescopes that significant progress will be made by high-spectral-resolution detectors in space, including those employing heterodyne techniques.

Another subject of considerable interest is that of isotopic fractionation, which may provide the most accurate "fingerprints" of interstellar processes that are preserved in comets and primitive asteroids. Low-temperature interstellar clouds lead to strong fractionation effects, especially with regard to deuterium/hydrogen (HD/H_2) abundance ratios in trace species. For example, although the interstellar abundance ratio HD/H_2 is approximately $1–2 \times 10^{-5}$, the abundance ratio between other deuterated species and their hydrogen analog can be higher than 0.01 in cold clouds. This effect is understood theoretically and occurs because the reactions between molecular ions and neutral molecules that dominate the chemistry at low temperature (ion-molecule reactions) can only proceed rapidly in exothermic directions. More systematic observations of selected fractionation ratios as functions of cloud temperature and density are required to refine current theories further. Once these theories have become more quantitative, theoretical treatments of how these isotopic ratios can be preserved as the interstellar cloud becomes a protosolar nebula will be most useful.

Some studies of the variations in abundance of selected species as functions of position and physical conditions within clouds are under way. For example, radio astronomers have begun to probe selected regions in the Orion nebula, a prototype giant molecular cloud. A variety of chemically unusual regions, associated to a greater or lesser extent with star formation, have already been delineated. It would be of interest to devote similar attention to lower-mass clouds such as TMC-1 and L183, because such smaller and colder regions may lead upon collapse to solar-type stars.

Complementary to the studies discussed above are broad surveys of the radio line spectra of interstellar sources: knowledge of the radio frequency spectra of most molecular clouds is extremely patchy. Systematic maps of the spectra have thus far been partially accomplished for only two giant interstellar clouds, that in Orion and one near the galactic center. These surveys, which detected on the order of 1000 emission lines, have resulted in a significant increase in the amount of chemical information available (see Figure 2.1). A similar survey of the dark cloud TMC-1 would be most worthwhile because it is a precursor of solar-type stars. Because clouds such as TMC-1 are so cool (10 K) and have little turbulence, spectral line widths are very narrow, making a survey much more difficult than in the giant clouds. To survey TMC-1 over a wide range of frequencies, a broadband high-resolution spectroscopic capability is required. Some of the instrumentation being developed in the SETI program may be useful here

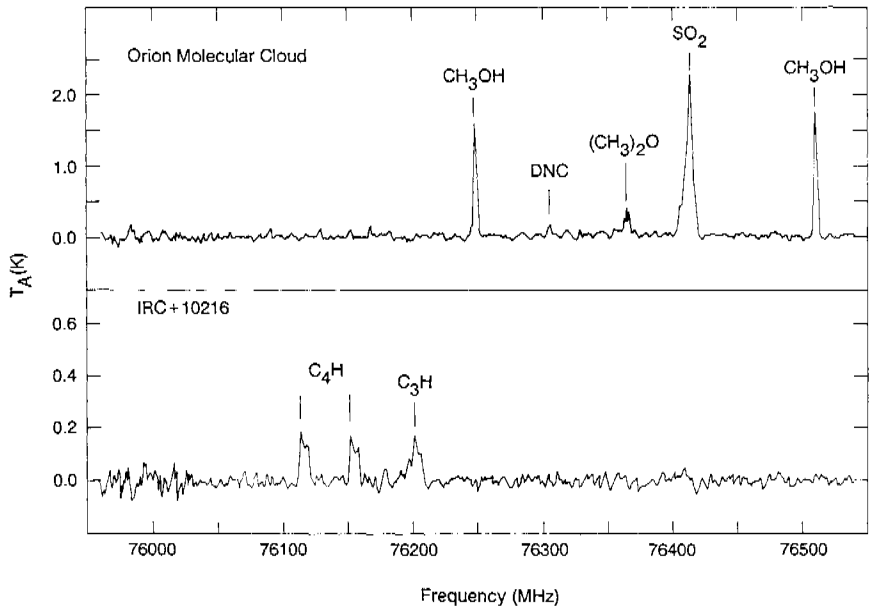

FIGURE 2.1 Portions of the millimeter wavelength spectra of a dense interstellar cloud (Orion) and the envelope around an evolved star (IRC+10216).

(Astronomy and Astrophysics for the 1980s, National Research Council, 1982, 1983a,b).

In the long run it is essential to broaden such studies to include a large sample of clouds. Will other abundance patterns be found? Will evolutionary effects on chemical composition emerge? Then, eventually, can the analogous chemistry be probed in external galaxies?

COMPLEX MOLECULES

Biochemistry is clearly the chemistry of large, complex, organic molecules. The largest molecule unambiguously observed in the gas phase of interstellar and circumstellar clouds is $HC_{11}N$. Although infrared spectra provide evidence for far larger species (such as polycyclic aromatic hydrocarbons; see discussion following objective 2), specific molecules have not been identified from the existing low-resolution spectra. To extend gas-phase high-resolution radio astronomical methods to search for molecules considerably larger than 13 atoms will require continually improving electronics and a strategy involving laboratory studies. The laboratory work is necessary because many species more complex than 13 atoms have not been

studied spectroscopically in the gas phase, especially in the radio and millimeter wave regions where their characteristic rotational transitions lie. The larger a molecule, the higher is its density of rotational levels, so that the intensity available in a single transition diminishes. Thus, to observe single rotational transitions of complex molecules in interstellar sources will require more sensitive instrumentation and large amounts of searching time. In addition, as molecules grow in complexity, their most intense spectral lines shift toward lower frequencies. Current plans to enhance the capabilities of the large (300 m), low-frequency radio telescope at Arecibo to include the 1- to 8-GHz frequency range would seem to be a boon for complex molecule studies.

Another important component of a strategy for determining the extent of molecular complexity in interstellar and circumstellar sources involves chemical modeling. Such modeling can tell astronomers what likely molecules may be found in a given environment and what intensities can be expected. From successful models involving smaller molecules, it is safe to say that much of the chemistry of the cold interstellar gas is accounted for by schemes based on gas-phase ion-molecule reactions which, because they typically possess no activation energy, can occur rapidly even at low temperature.

Although models of interstellar clouds involving small gas-phase molecules are in good agreement among themselves and with observation, they differ significantly in their predictions of complex molecule abundances. These differences derive at least in part from lack of laboratory data on important ion-molecule reactions. Thus, an additional component of the strategy emerges—the need for laboratory work on important ion-molecule reactions to aid modelers in calculating the expected abundances of complex molecules. Nor is this the final element of such a strategy: chemical models cannot be based entirely on laboratory studies of relevant reaction rates. Reaction systems with rate coefficients that are highly temperature dependent, which have only been studied in the laboratory at approximately room temperature, may occur at unsuspected rates under interstellar conditions. In addition, some classes of reactions are not easily studied in the laboratory. An example is the low-pressure process called radiative association, which is thought to be critical in gas-phase syntheses of complex molecules. To examine this and other processes requires theoretical studies of rate coefficients. Such studies are then another integral part of a strategy aimed at determining the limits of molecular complexity in interstellar and circumstellar sources.

Although the tenor of the discussion on interstellar chemistry has been concentrated on gas-phase processes, the influence of dust particles cannot be ignored. These particles are sites of molecular adsorption, desorption, and possible reactions, and they can protect complex molecules from stellar ultraviolet radiation. Further discussion of particulate matter is given after objective 2 (see below).

In general, modeling of circumstellar sources has lagged somewhat behind that of interstellar ones. However, within the last few years, several circumstellar models have become available. The picture of carbon-rich circumstellar sources such as IRC+10216 that emerges is one in which chemical equilibrium at high temperature is achieved as material is ejected from the star, only to be reprocessed by an active photochemistry and ion-molecule reactions as the material proceeds further from the stellar photosphere. Significant amounts of complex molecules may be produced by these processes.

STAR-FORMING REGIONS AND THE SUBMILLIMETER SPECTRAL RANGE

How is the chemistry of an interstellar cloud affected by the process of star formation? Virtually nothing is known in this regard for isolated solar-mass stars. For more massive stars, however, some evidence has been obtained from study of the Orion nebula. Astronomers have thus far detected at least three unusual regions in which the abundances of gas-phase molecules are quite different from more normal values. Suggested causes include chemical reactions driven by shock waves, molecules desorbed from the interstellar grains by temperatures exceeding 100 K, and interactions between species so produced and the "normal" constituents of the ambient cloud. As more information becomes available concerning the unique chemistry of star-forming regions, it should be possible to develop models of their chemistries with some predictive power. Indeed, primitive models of the star-forming regions in Orion are currently being formulated.

Detailed observational studies of small regions warmer than the ambient interstellar medium will require very high angular resolution, which must be obtained by interferometric techniques. Expansion of existing facilities and eventual construction of instruments such as the Millimeter Array and the Submillimeter Array Telescope being discussed by the National Radio Astronomy Observatory (NRAO) and the Smithsonian Astrophysical Observatory (SAO), respectively, will be required. In addition, frequencies higher than those normally used, particularly in the submillimeter region, are important. Because, as the temperature rises, the dominant rotational line emission of most smaller molecules shifts into this wavelength region. Moreover, some light molecules such as simple hydrides can be observed only in the submillimeter spectral region; some of these species are critical to a quantitative understanding of chemical processes in interstellar clouds (e.g., the ion H_3^+ and metal hydrides such as MgH). Unfortunately, severe problems are associated with submillimeter observations. Ground-based observation is extremely difficult because of atmospheric water. Although a first generation of ground-based submillimeter telescopes is currently being constructed in high, dry locations, the advantages to observing this spectral

region from space are enormous (e.g., with LDR and SIRTF). An equally important problem, however, is the small laboratory data base on which submillimeter astronomy can draw. Very few gas-phase molecules have been examined in the submillimeter region; many more studies are needed. Thus, a necessary component of a strategy aimed at using this spectral range to study star-forming regions involves laboratory spectroscopy.

To achieve the recommendations listed below, it will be necessary for exobiologists to interact closely with the astronomical and planetary science communities. The committee supports the major recommendations of the Astronomy Survey Committee (*Astronomy and Astrophysics for the 1980s*, Volume 1, National Research Council, 1982) to construct an LDR in space to carry out spectroscopic and imaging observations in the far-infrared and submillimeter wavelength regions of the spectrum that are inaccessible to study from the ground. Such an instrument, in the 10-m class, will offer unprecedented opportunities for studying the molecular and atomic processes that accompany the formation of stars and planetary systems. The committee also concurs with the recommendation from *A Strategy for Space Astronomy and Astrophysics for the 1980s* (SSB, 1979) that development of a meter-class, cryogenically cooled, infrared telescope be actively continued, with the option of its construction as a free-flying spacecraft being retained until the Shuttle environment has been demonstrated to be sufficiently free of contaminants (SIRTF).

OBJECTIVE 2: *To determine the composition, structure, and interrelationships among circumstellar, interstellar, and interplanetary dust.*

Interstellar grains constitute an important component of the interstellar medium. They play a crucial role in the heating and cooling of interstellar clouds through the absorption of visible and ultraviolet photons and the ejection of energetic photoelectrons. They also influence the gas-phase composition of molecular clouds directly by providing surfaces for reactions and indirectly by locking up some elements, as well as by shielding molecules from the dissociative ultraviolet interstellar radiation field. Observations have shown that these dust grains have a size distribution ranging from approximately 3000 Å down to perhaps molecular sizes and that they lock up a large fraction (≥90 percent) of some heavier elements such as silicon, iron, calcium, and aluminum, as well as a substantial fraction of the available carbon, nitrogen, and oxygen.

The life history of interstellar grains is a complex interplay of many different competing processes, including nucleation and condensation around stars and accretion, chemical modification, and shock processing in the interstellar medium. Some interstellar grains ("star dust") originally condensed in the high-density, high-temperature environment ($n \approx 10^8$ cm^{-3}; $T \approx$ 1000 K) of the circumstellar envelopes of red giants, planetary nebulae, and

novae and have subsequently been expelled into the interstellar medium along with gaseous species. Other possible dust components may originate in the interstellar medium itself by accretion, reaction, and photolysis of gaseous species on preexisting grain cores. Laboratory experiments suggest that a C_{60} spherical molecular species "fullerene" may also be a component of interstellar dust. Table 2.2 contains a summary of current knowledge of the composition of interstellar dust. There is at least some evidence for all of the dust components shown in circumstellar or interstellar environments, mainly through low-resolution infrared spectroscopy (see below).

Silicate grains are a ubiquitous component of the dust in the diffuse ($n \leq 10^2$ cm^{-3}) interstellar medium, and this star dust component may actually make up about half the interstellar dust volume (cf. Table 2.2). On the basis of elemental abundances and stability, the remainder of the dust volume has to consist of species containing predominantly carbon. However, it is still an open question whether this carbon is in the form of graphite, which would likely be a star dust component, or in the form of refractory organic grain mantles, which might form via processes in the interstellar medium. Although small graphite particles (≈200 Å) may be the carriers of the ubiquitous 2200-Å bump in the ultraviolet spectra seen toward stars, large graphite grains (1000 Å) do not possess any currently detectable infrared or ultraviolet absorption features; thus, we can only guess at their contribution to the interstellar dust volume.

Icy grain mantles, consisting of simple molecules such as H_2O, CO, and perhaps NH_3 and CH_3OH (methanol), are an important component of interstellar dust inside dense molecular clouds, but they have never been observed in the diffuse interstellar medium. Traces of more complex organic molecules (e.g., aldehydes, ketones, and nitriles) have also been reported in some objects. Icy grain mantles are presumably formed by the accretion of gas-phase species onto preexisting cores inside molecular clouds. In the less dense interstellar medium, these volatile materials would be efficiently destroyed by photodesorption and subsequent photodestruction in the interstellar ultraviolet radiation field and by shock waves. Inside dense molecular clouds the much lower ultraviolet flux—from embedded newly formed stars or from cosmic-ray excitation of molecular hydrogen—may be sufficiently high to transform the simple icy molecules into more complex molecules, which are more refractory. This process may also be the source of the more refractory grain mantles possibly observed in the diffuse interstellar medium.

GRAIN INTERRELATIONSHIPS

The evolution of biogenic elements in the interstellar medium prior to the formation of the solar system has gained additional interest with the

TABLE 2.2 Possible Interstellar Dust Components

Component	Structure	Birthsite	Elemental Abundance[a]	Relative Volume[b]	Spectral Signature
Silicates	Amorphous	Oxygen-rich giants and novae	100% Si; 20% O (Mg and Fe?)	1	10- and 20-μm features
Graphite	Crystalline	Carbon-rich giants (?)	≥25% C	≥0.25	2200-Å bump[c]
Polycyclic aromatic hydrocarbons	Molecular species	Carbon-rich planetary nebulae	1% C	0.01	3.3-, 6.2-, 7.7-, and 11.3-μm emissions features
Amorphous carbon	Polycrystalline	Carbon-rich giants	5–10% C	~0.08	7.6-μm absorption feature
Icy grain mantles[d]	Amorphous	Molecular clouds and O[d]	≤40% C	≤2.8[d]	3.08-, 3.4-, 4.67-, 4.9-, 6.0-, and 6.85-μm absorption features
Organic refractory grain mantle[e]	Amorphous polymer	Interstellar medium	25% C, 6% O[e]	~0.8[e]	3.4-μm absorption feature
SiC	Crystalline	Carbon-rich giants and planetary nebulae	—[f]	—[f]	11.4-μm emission feature
MgS	Crystalline	Carbon-rich giants and planetary nebulae	—[f]	—[f]	30-μm emission feature

[a]Percentage of the cosmic abundance of an element locked up in a dust component in the interstellar medium in this model.
[b]Volume of a dust component relative to that of silicates.
[c]Only graphite grains with a size of about 200 Å will contribute to this bump.
[d]This dust component is ubiquitous in molecular clouds but has not been observed in the general interstellar medium.
[e]This dust component has been observed only toward the galactic center, but it might be more widespread (see text).
[f]This dust component has not (yet) been detected in the interstellar medium.

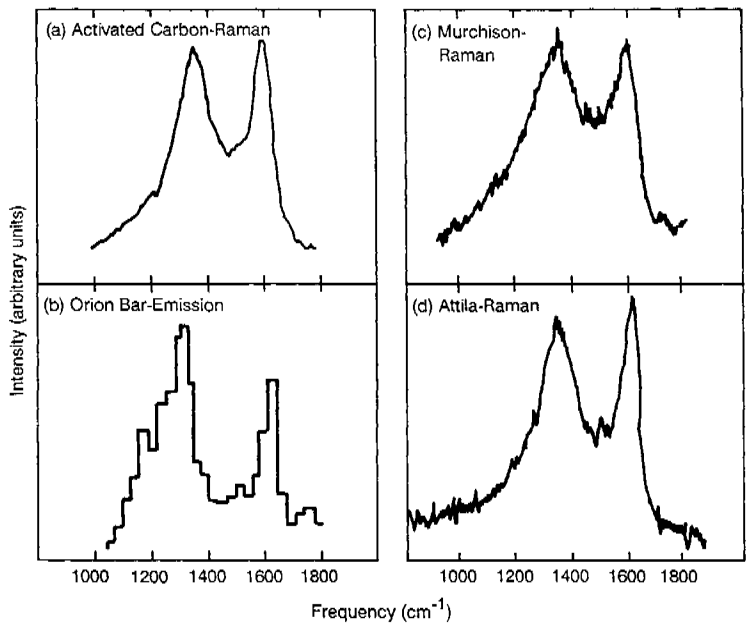

FIGURE 2.2 Infrared spectra of (a) soot derived from automobile exhaust, (b) the Orion molecular cloud, (c) a carbonaceous chrondritic meteorite, and (d) an interplanetary dust particle.

discovery in recent years that presolar grains have apparently been incorporated into meteorites without totally losing their identity (see discussion following objective 4 below). An interrelationship among circumstellar, interstellar, and interplanetary dust is supported by a comparison of infrared and Raman spectra from such sources. For example, Figure 2.2 shows the midinfrared spectrum observed toward the prominent ionization bar in the Orion nebula (interstellar cloud), in which the emission has been ascribed to infrared fluorescence of interstellar polycyclic aromatic hydrocarbon molecules (hereafter PAHs) pumped by the absorption of energetic ultraviolet photons from nearby embedded stars. Similar midinfrared spectra have been observed toward reflection nebulae, carbon-rich planetary nebulae, and some galactic nuclei. Presumably, these PAHs are the extension of the size distribution of interstellar carbon grains into the molecular domain, and these large molecules are formed as the condensation nuclei of carbon grains in the circumstellar outflow of carbon-rich planetary nebulae and red giants. The observed interstellar infrared spectrum is compared in Figure 2.2 to the laboratory-measured Raman spectra of carbonaceous grains in interplanetary dust particles, carbonaceous chondrites, and auto exhaust. The striking

similarities among these spectra illustrate the structural similarities in these different types of cosmic grains. In addition, the discovery both of anomalously low $^{12}C/^{13}C$ ratios in a refractory carbon phase in meteorites, and of isotope ratios attributable to discrete nucleosynthetic (stellar) sources for noble gases trapped within meteoritic carbonaceous grains, suggests an origin in red giants for these grains. This means that some interstellar carbon grains have been carried into the solar system and incorporated into larger bodies. Similar evidence from the deuterium-to-hydrogen ratio in some components of carbonaceous meteorites is discussed following objective 4 below. Strengthening and extending the possible interrelationships among circumstellar, interstellar, and interplanetary dust should be an important goal for the near future. Because other interstellar dust components may also have survived incorporation into the presolar nebula, it is important that searches be conducted for interstellar or circumstellar signatures for the biogenic elements in other primitive interplanetary, meteoritic, or cometary dust components such as silicates, carbides, and ices.

INFRARED SPECTROSCOPY AND ASTRONOMY

As already demonstrated, infrared spectroscopy is a useful tool for studying the composition of cosmic dust. Broad emission and absorption features often appear superimposed on the midinfrared thermal continua of interstellar and circumstellar emission regions. These features are due to vibrational transitions in solid materials or large molecules and can be used to identify the functional groups present. Infrared spectroscopy has already been used to infer, to varying degrees of certainty, the presence of silicates, icy grain mantles (e.g., solid H_2O, NH_3, CO, and CH_3OH), PAHs, silicon carbide (SiC), magnesium sulfide (MgS), organic refractory grain mantles, and possibly amorphous carbon in interstellar and circumstellar objects (cf. Table 2.2). Future work should concentrate on characterizing the molecular complexity of icy grain mantles inside dense molecular clouds and the possible organic refractory grain mantles in the diffuse interstellar medium. In this respect it is particularly important to investigate further any evolutionary relationship. Another line of research should be the search for deuterated molecules in these dust components, because this information may confirm the possible link between interstellar grains and components of meteoritic and interplanetary dust. Such studies, down to a D/H enrichment of 10^3 over cosmic levels, are possible with present or near-future instrumentation for the most abundant molecules.

Special emphasis should be given to regions with evidence for proto- or postplanetary disks (e.g., Vega and β Pictoris). Except for interplanetary particles, little is presently known about the isotopic and biogenic element composition of dust in protostellar nebulae. Emission by warm silicate

grains is commonly observed around newly formed stars. In addition, ice absorption features are also observed toward embedded infrared sources (protostars?), but they are generally caused by very cool (10 to 50 K) dust in the intervening parental molecular cloud rather than by dust in the putative collapsing protostellar envelope or the protoplanetary disk. This is partly because of the large beam size of existing observations (~1′, corresponding to 10^4 AU at the distance of the nearest sources of star formation). Infrared Astronomical Satellite (IRAS) and Kuiper Airborne Observatory (KAO) studies have shown the usefulness of far infrared for the detection of protostellar and protoplanetary disks around protostars and main sequence stars; nevertheless, higher angular resolution is an important goal.

Because important parts of the 2- to 1000-μm spectral region are blocked by atmospheric absorption, even from airborne altitudes, space-based observations are required. These have the added advantage of cryogenic cooling and thus of lower background. The resulting higher sensitivity will permit observations of weaker infrared sources. Given the expected width of absorption and emission features, a resolution ($\lambda/\Delta\lambda$) of about 3000 is necessary to study the grains, whereas even higher resolution is required for observations of the gas phase. The composition of interstellar, circumstellar, and protostellar dust is very complex and probably varies from object to object. Observations of many different objects and correlation of their observed absorption or emission features, supported by theoretical and laboratory studies, will be required to unravel this complexity and to identify the molecular constituents responsible. Although in the long-term, space-based infrared observations (as would be provided by SIRTF) are called for and efforts should be directed at preparing for such endeavors, in the short term, characterization of the dust through ground-based as well as airborne infrared observations should continue. Higher resolution ($\lambda/\Delta\lambda > 200$) than presently used for such studies is an important near-term goal. Further improvements in sensitivity will be possible when larger ground-based or airborne telescopes become available. Continued analysis of the IRAS data base is also important. Despite the rather poor spectral resolution ($\lambda/\Delta\lambda$ = 10 to 40), the 8- to 22-μm spectra obtained with IRAS have already yielded valuable new insights into the properties of interstellar and circumstellar dust.

The electronic transitions that dominate the visible and ultraviolet spectra of solid materials are very characteristic of their chemical composition and structure. However, it should be noted that the sizes of interstellar and circumstellar grains are comparable to wavelengths in the visible and ultraviolet spectral regions. Size and shape effects will then influence the observed spectra. In particular, the presence of a grain size distribution will tend to smear out spectral structure and, therefore, hamper the characterization of grains. Nevertheless, because of the possible unique interpretation,

studies of structure in the visible and ultraviolet spectral regions are very important and should be pursued further. Of particular importance is the search for spectral structure in the ultraviolet region, which will become possible with the launch of the Hubble Space Telescope. Visible and ultraviolet studies can also give indirect information on the composition of interstellar dust through studies of gas-phase depletion of the biogenic elements.

These observational projects require much supporting laboratory and theoretical effort. For successful interpretation of interstellar spectra, laboratory studies should include infrared spectroscopy of candidate molecules (e.g., PAHs) and molecular ice mixtures. Also important are experimental studies on interstellar grain chemistry, including grain surface chemistry as well as the effects of ultraviolet photolysis and transient heating on the composition of interstellar grain mantles. Studies of the condensation process in the outflow from late-type giants, planetary nebulae, novae, and supernovae should be undertaken. Special emphasis should be given to isotopic enrichments during the condensation process, including those of trace noble gases trapped in the solid phase. Correlation studies with grains identified in primitive solar-system materials, including carbonaceous chondrites, interplanetary dust particles, and cometary materials, will be able to elucidate the possible interrelationships among interstellar, circumstellar, and interplanetary grains.

Finally, the possibility of cosmic dust collection in earth orbit should be mentioned. This is, of course, of primary concern for the collection of meteoritic and cometary debris, but if such instrumentation were able to measure the orbital elements of collected dust particles, then interstellar dust particles could be separated from interplanetary ones. The possibility of studying actual interstellar grains in the laboratory rather than by remote sensing is an exciting prospect and would undoubtedly revolutionize our knowledge of interstellar grains and their connection with primitive interplanetary particles.

OBJECTIVE 3: *To assess the efficacy of chemical and physical processes in the solar nebula for altering preexisting materials and producing new compounds and phases containing the biogenic elements.*

The collapse of one particular interstellar cloud led to the formation of a flattened disk of dust and gas that is referred to as the solar nebula, in which the Sun and planets formed. In currently accepted models of the solar nebula, radial temperature gradients are presumed to be a major influence on the composition of the gas and dust grains. These models indicate that as the interstellar gas and dust were accreted by the solar nebula, they were thermally and chemically equilibrated to varying degrees. Accreting gases may have been only partially equilibrated (or not at all) as they were warmed and compressed. The extent to which this occurred would be de-

pendent on the distance of the gas parcel from the protosun and the rate of radial transport in the nebula relative to the rate of equilibrating reactions in the gas parcel. Similar considerations apply to the accreted interstellar dust grains. Recent theoretical work suggests that accreting dust grains may have evaporated totally, partially, or not at all, depending on the type of grain, the strength of radial mixing in the nebula, and the distance from the protosun. Isotopic data for the primitive calcium- and aluminum-rich inclusions (CAIs) in the Allende carbonaceous chondrite imply that the CAIs formed by a complex sequence involving condensation, partial evaporation, and recondensation. Such observations and theoretical models strongly suggest that evaporation and recondensation leading to thermal and chemical equilibration were very probable in the inner regions of the solar nebula. The net result of these processes would have been the alteration and reprocessing of any existing compounds and phases containing the biogenic elements (except possibly for very refractory "graphitic" phases).

However, these arguments become less and less convincing with increasing radial distance (and thus lower temperature) in the solar nebula. Again, inferences from meteorites are instructive. The observed isotopic anomalies in several biogenic elements (e.g., H, C, N, O) in the volatile-rich carbonaceous chondrites imply that interstellar material (or at least its chemical and physical signature) is preserved in these meteorites. This result contrasts with the "standard" chemical model of the solar nebula, which assumes complete evaporation and recondensation of the grains and complete chemical equilibration of the gas and dust.

The two most important conclusions of such a standard model are (1) that the solid grains that equilibrated at lower temperatures (i.e., farther from the protosun) are predicted to contain more biogenic element-bearing phases and to be more rich in volatiles than the solid grains equilibrated closer to the protosun, and (2) that the biogenic element-bearing phases are predicted to be simple molecular compounds such as H_2O (either as water ice or as bound water in hydrated silicates), NH_3 or NH_3 hydrates, and CH_4 or CH_4 clathrate hydrate. Other biogenic elements such as sulfur or phosphorus are predicted to be retained in the solid grains in the form of solutions in iron-nickel (Fe-Ni) alloys, as sulfides or phosphides of Fe-Ni, or as phosphate minerals.

Although the major predictions of this equilibrium model for the bulk composition of planetary-forming materials are consistent with observations of the terrestrial planets and the asteroids, several important facets of the chemistry of the biogenic elements (in addition to isotopic anomalies) cannot be accommodated within the framework of this model. In particular, the atmospheric inventories of CO_2 on Venus and Earth, and of N_2 (gaseous nitrogen) on Venus, Earth, and Mars, are larger (substantially so in the case of N_2) than the inventories predicted by the complete equilibrium model.

Likewise, carbonaceous chondrites may contain several percent (by mass) of organic material, which is the dominant reservoir of carbon and nitrogen in these meteorites. Neither the relatively large abundance nor the complex molecular structure of the carbon- and nitrogen-bearing phases can be accounted for by the complete equilibrium model. Indeed, the occurrence of oxidized carbon molecules such as CO and CO_2, which have been observed in comets, also cannot be explained by this model. It is therefore necessary to explore nonequilibrium effects on the chemistry of the biogenic elements and compounds in the solar nebula.

Among the various nonequilibrium processes pertinent to the solar nebula, more research has been done on thermal effects associated with cooling than on other processes such as shock heating, ultraviolet irradiation, solar flares, and lightning. Understanding the effects of these latter processes on the chemistry of the biogenic elements and compounds is important, and much more effort should be devoted to their investigation.

Nonequilibrium thermal effects in a cooling parcel of gas and dust in the solar nebula will be favored when the characteristic cooling time (or the characteristic radial mixing time) is less than the characteristic chemical time scales for the gas-phase (t_g), gas-solid (t_{gs}), and solid-solid (t_{ss}) reactions that may occur inside this parcel. If the characteristic cooling time is t_c, this condition can be expressed by the inequalities $t_c < t_g$, $t_c < t_{gs}$, and $t_c < t_{ss}$. These inequalities will be favored by low temperatures, fast nebular cooling rates, and fast radial mixing times; for reactions involving solids, the inequalities will also be favored by large grain sizes and fast accretion rates for these grains.

How will nonequilibrium thermal effects influence biogenic element chemistry? Some insight into this question can be achieved by considering two reactions that exemplify biogenic element retention by solid grains in a cooling parcel of gas and dust in the solar nebula. First, consider solid-solid reactions: these are likely to be the most sluggish and hence the most susceptible to nonequilibrium effects. The retention of H_2O as the hydrous mineral serpentine proceeds by the reaction

$$Mg_2SiO_4(s) + MgSiO_3(s) + 2H_2O(g) = Mg_3Si_2O_5(OH)_4(s),$$

which, because it requires the transport and reaction of elements between two minerals, may proceed very slowly at low temperatures (400 K) where serpentine is thermodynamically stable in the solar nebula. If this is the case, then $t_c << t_{ss}$ may hold, and in the absence of "fast" pathways for forming equal amounts of other hydrated phases, H_2O may not be retained in solid grains until below 200 K, when H_2O ice becomes stable. This has significant consequences for H_2O retention by the terrestrial planets and implies that H_2O must be delivered to these planets by icy planetesimals and comets gravitationally scattered in the inner solar system during the

later stages of planetary accretion. It may be shown that a similar conclusion applies to these planets' sulfur inventories.

An exemplary gas-gas reaction is the conversion of CO to CH_4:

$$CO(g) + 3H_2(g) = CH_4(g) + H_2O(g).$$

Kinetic inhibition of the conversion of CO to CH_4 has in fact been studied quantitatively; for estimates of the nebular cooling time t_c consistent with estimates of the nebular lifetime, and for estimates of the nebular radial mixing time t_m consistent with subsonic radial mixing, only a few percent of the available CO can be converted to CH_4 before this reaction is quenched. However, in this instance the failure to achieve equilibrium may make the retention of carbon by planetary-forming materials in the inner regions of the nebula easier instead of more difficult. The homogeneous gas-phase conversions between CO and CO_2 can continue down to relatively low temperatures, leading to the presence of several percent of carbon as CO_2—in fact, more carbon can be present as CO_2 than as CH_4. In turn, the CO_2 can condense as a solid or it can undergo further reactions with H_2O leading to the formation of a clathrate hydrate or reactions with NH_3 leading to the formation of either ammonium bicarbonate (NH_4HCO_3) or ammonium carbamate ($NH_4CO_2NH_2$). The latter two species would be readily incorporated into the first H_2O-ice-rich condensate, providing four major biogenic elements (H, C, N, O) and the presence of an aqueous phase in small bodies such as comets and asteroids. Also, the presence of metastable CO inside the CH_4 stability field leads to supersaturation of elemental carbon in the gas phase, which can be relieved by the formation of organic material, as in the Fischer-Tropsch reaction, or by shock heating from lightning.

In fact, the implications of the failure to achieve chemical equilibrium between nebular gas and grains are important in a much broader context. For example, if the accreting interstellar gas is *not* chemically equilibrated before the condensable components of this gas are incorporated into solid grains, then the chemical and isotopic diversity present in this fraction of the gas will be preserved until some point in the future—perhaps until a volatile-rich cometary body impacts the Earth. Given the relative rapidity of gas-solid condensation reactions (especially when "rocky" condensation nuclei may already be present in the outer regions of the solar nebula) and the sluggishness of molecule-molecule and molecule-radical reactions at the low temperature (<100 K) predicted, in the outer solar nebula, nonequilibrium effects may be the rule rather than the exception.

Other inherently nonequilibrium processes, such as photochemistry, solar flares, lightning, coronal discharges, and planetesimal impacts, must also be considered for their influences on biogenic element chemistry in the solar nebula. In general, the net effect of such processes will be to increase molecular complexity and diversity over that expected if the chemistry of

the biogenic elements were allowed to approach equilibrium. For example, observations of young (T Tauri) stars suggest that the early Sun's ultraviolet flux may have been enhanced by a factor of 10^4 relative to the present-day flux. If this enhancement factor and a nebular lifetime of 10^6 years are assumed, then the potential number of molecular dissociations produced by this early enhanced ultraviolet flux would be equal to the number of molecules in a solar composition nebula of approximately 10 solar masses.

The ultraviolet flux from nearby stars is also a potential nonequilibrating mechanism in the solar nebula. Although the corresponding flux from the early Sun is orders of magnitude greater and may lead to a larger number of molecular dissociations, subsequent pyrolysis of the product molecules in the hot inner regions of the solar nebula may lead to a very small overall net yield of nonequilibrium species (e.g., both simple and complex organic compounds). On the other hand, the relatively smaller number of photochemically pumped molecular dissociations in the outer regions of the solar nebula that are shielded from the Sun by particulate matter in the nebula itself may give a larger net yield of nonequilibrium species due to the absence of efficient thermochemical loss mechanisms for the product molecules.

The production of nonequilibrium species by solar flare irradiation and rapidly quenched high-temperature shocks, such as those associated with lightning and with planetesimal impacts, will also increase the molecular complexity and diversity of biogenic-element compounds present in the solar nebula. Little quantitative modeling or laboratory simulation has been done for these potentially important processes. However, the modeling and simulation that have been done for lightning, coronal discharges, and impacts on the primitive Earth and on the outer planets show that HCN (hydrogen cyanide) and H_2CO, which are important precursors in the synthesis of more complex organic compounds, can be produced with relatively high efficiencies from gas mixtures of H_2O, CH_4, and NH_3. More work on the effects of solar flare irradiation and high-temperature shock chemistry on the biogenic elements and their compounds in a nebular environment is desirable to explore these attractive possibilities.

It is necessary to do theoretical modeling of nonequilibrium effects on important gas-solid and solid-solid reactions responsible for the retention of biogenic-element-bearing phases in planetary-forming materials. Perhaps the single most important class of reactions to be studied is that responsible for incorporating H_2O into planetary-forming materials. The thermochemical reactions responsible for the conversions of solid carbonaceous phases, "reduced" carbon-bearing gases, and "oxidized" carbon-bearing gases also deserve detailed quantitative modeling. Although sufficient basic data on some chemical reaction rates and pathways are currently available, in other instances new laboratory studies of chemical reaction rates are necessary to

obtain the date for theoretical modeling. Kinetic data are specifically needed for homogeneous gas-phase kinetics of the conversion of reduced and oxidized phosphorous compounds, and heterogeneously catalyzed kinetics for the conversion of reduced and oxidized carbon compounds.

It is also important to use realistic laboratory simulation experiments and quantitative theoretical modeling to study the effects of photochemically pumped nonequilibrium chemistry on the biogenic elements and their compounds under pressure, temperature, composition, and photon flux conditions consistent with currently accepted models of the solar nebula. In this regard it would be particularly valuable to try to simulate the effects of the ultraviolet flux from nearby stars on the gas-solid distribution of the biogenic elements carbon, nitrogen, sulfur, and phosphorus between a cold solar composition gas and the grains embedded in it. The use of different substrate types (e.g., "rock," metal, and carbonaceous or graphitic material) for the simulated grains is also recommended. These experiments may yield important insights into the chemical processes affecting the biogenic elements in the outer regions of the nebula where thermochemical reactions were (probably) unimportant.

Finally, the use of realistic laboratory simulation experiments should be extended to the study of other nonequilibrium processes affecting the biogenic elements and their compounds in the solar nebula. Such processes include the production of organic compounds by the rapid quenching of high-temperature shocked gas mixtures (as in corona discharges, lightning, or planetesimal impacts), the gamma radiolysis of $CO—CO_2—H_2—Fe_{2+}$ mixtures, and Fischer-Tropsch reactions. If simulations under conditions of pressure, temperature, composition, and energy input consistent with currently accepted models of the solar nebula are impractical, then every effort should be made to conduct experiments under conditions that permit extrapolations to model conditions with a high degree of confidence.

OBJECTIVE 4: *To determine how the formation and evolution of primitive bodies modified the distribution, structure, and composition of preexisting compounds and solid phases containing the biogenic elements.*

GRAIN INTERACTIONS

The earlier objectives discussed chemical processes in the gas and grains of the solar nebula. Here, the physical growth of these grains into large objects and the chemical changes corresponding to such growth are considered.

The formation and development of primitive bodies encompass a wide spectrum of processes from the gentle amalgamation of micron-sized dust particles into larger aggregates to the differentiation of metals, silicates, and

volatiles in asteroidal objects. Depending on the accretion conditions and the geological evolution of their host bodies, the records of attendant alterations in the distribution, structure, and composition of the gases and grains inherited from the solar nebula would have been preserved with varying degrees of integrity. Some processes would have given rise to new compounds and solid phases, and these may testify to the earliest analogues of prebiotic processes that occurred later in the first 700 million years on the terrestrial planets but for which no geological record is accessible.

For present purposes it is convenient to consider three stages in the development of primitive bodies: (1) coagulation of nebular dust into centimeter-sized aggregates, (2) formation of kilometer-sized planetesimals, and (3) accretion of planetoids tens to hundreds of kilometers in diameter (i.e., asteroid-sized objects). Very few observational or experimental data exist regarding the first two stages, although some evidence may be uncovered through studies of meteorites, asteroids, comets, and interplanetary dust particles (IDPs).

In the first stage of this process, the complex interplay of grain-grain and gas-grain interactions would have established a balance between growth and destruction such that a significant number of aggregates in the range of 0.1 to 10 cm could have formed, even though most of the mass of dust would have remained in the micrometer range.

During particle growth, adsorption and eventual trapping of volatiles (including noble gases) within the aggregates could have taken place, thus preserving a record of the gas composition of the solar nebula. Such entrapment has been suggested to account for the noble gases in primitive meteorites, the bulk of which reside in carbonaceous grains. Chemical and isotopic fractionation also could have occurred as a result of the separation of dust and gas. For example, if the bulk of any of the biogenic elements resided in dust, then their concentrations would have been strongly enhanced in the equatorial plane of the nebula, and they would have been preferentially incorporated into planetesimals.

The growth of particles by accretion would have depended on their composition and structure, other factors being equal. The sticking of particles to each other involves short-range van der Waals, electrostatic, or ferromagnetic forces, of which van der Waals forces are expected to be the most important for nonmetallic grains. In this regard, it has often been suggested that the "stickiness" of organic matter may have facilitated grain growth in the early solar system. In a similar vein, it may be expected that accretion would be less favorable in collisions between hard compact grains than in interactions between relatively soft and porous deformable ones. Both of these hypotheses imply a critical role for the biogenic elements in facilitating the earliest stages of the formation of solid bodies, but neither has been tested by experimental observations.

Relics of kilometer-sized planetesimals formed in the second stage of development may still be preserved as small comets in the Oort cloud, and it has been suggested that the geomorphology of Comet Halley shows signs of formation through impact accretion of cometesimals in this size range. Similarly, evidence of planetesimals formed closer to the protosun than Jupiter may be found in the asteroid belt, and variations in their chemical composition with heliocentric distance may reflect the distribution of biogenic elements in planetesimals during this stage.

Based on modeling studies, the formation of planetoid-sized primitive bodies began with the relatively gentle collisional aggregation of planetesimals and smaller objects in nearly circular orbits. As some bodies grew to planet size and became large enough to perturb the trajectories of smaller objects in their vicinity, the remaining planetoids would have acquired more eccentric orbits and larger collisional velocities. Thus, accretion would have changed from a low-energy accumulation stage, which produced relatively homogeneous bodies, to one of higher energy involving a balance between shattering and accumulation, which mixed materials from a wide range of orbits and formation environments. Evidence of impacts is preserved throughout the solar system in the cratered surfaces of planets and their satellites, including the moons of Mars (Phobos and Deimos).

Repeated cycles of accretion, breakup, and continued growth would have produced surface regolith environments tens to hundreds of meters thick. Cooling times within thick regolith blankets could have been as long as hundreds of years. These processes would have mixed into the same body organic and inorganic materials from a variety of sources, including other bodies that had experienced separate evolutionary histories. Thus, materials oxidized and reduced, pristine and highly altered, and both rich and depleted in the biogenic elements may have been coaccreted. Such a diversity of materials—and, by implication, sources—is indeed found in carbonaceous chondrites, wherein, for instance, igneous mineral inclusions coexist with amino acids.

The possible fates of compounds and phases containing the biogenic elements in this stage of planetoid formation are many and diverse. To varying degrees of intensity, impacts could have caused pyrolytic decomposition of heat-sensitive organic matter to form both gaseous and refractory products, thermal and aqueous alteration of minerals and carbonaceous grains, melting, near-surface volatile transport, and loss of volatiles to transient atmospheres from either the target or the projectile. Ample observational evidence from the mineralogy of meteorites strongly suggests that virtually no parent body has escaped the effects of thermal metamorphism.

Moreover, the suite of hydrous minerals found in the volatile-rich carbonaceous chondrites has been shown to result from aqueous alteration of preexisting anhydrous assemblages in a regolith environment. How water,

carbon dioxide, and other volatiles were mobilized to accomplish this transformation is not known. In sharp contrast to the amount of evidence pointing to alteration effects on minerals, very little is known about what imprint these effects left on preexisting organic matter that accreted onto the parent bodies of carbonaceous and unequilibrated chondrites. Depletions in bulk abundances of hydrogen, carbon, and nitrogen in some ordinary chondrites have been attributed to thermal metamorphism; however, evidence also suggests that volatile elements were already depleted in the nebular dust that accreted to form the chondrites.

It is especially noteworthy that conditions could have existed within the regoliths or in transient atmospheres that were conducive to de novo synthesis of organic compounds and phases from the degradation products of preexisting material. Evidence of such synthesis is of the utmost importance because analogous processes undoubtedly occurred in *planetary* environments, and important insights into the prebiotic mechanisms of synthesis may be obtained through study of the organic matter in meteorites. A few measurements of the isotopic composition of carbon, hydrogen, and nitrogen in meteoritic hydrocarbons, amino acids, and carboxylic acids are consistent with parent body origins, but the data base must be enlarged to establish which compounds were produced in planetoid as distinct from presolar or nebular environments.

A comparable situation holds for the high molecular weight insoluble organic matter that contains the bulk of the carbon and nitrogen in primitive meteorites. This chemically heterogeneous material contains small amounts of isotopically anomalous hydrogen, carbon, nitrogen, and noble gases attributable to presolar origins, but the amount and nature of the material that may have been affected by alteration or synthesized on the parent bodies are poorly understood.

In contrast to the thermal regimes of near-surface environments, the interior temperatures of the planetoids are expected to have been affected in only a minor way by discrete accretionary events. If the overall time scale of accretion was short, however, the decay of surviving ^{26}Al (730,000-year half-life) could have melted objects as small as 1 km in diameter; over longer time scales, the decay of ^{40}K and the actinides (~10^9-year half-lives) would have heated the interiors. The actual heat sources responsible for the mobilization of fluids required for aqueous alteration, internal metamorphism, and igneous differentiation of planetoids in the early history of the solar system are unknown.

Maximum temperatures within the parent bodies of chondritic meteorites may not have exceeded 1000 to 1300 K, and the composition of metal alloys in these meteorites indicates parent body slow cooling rates on the order of 1 to 100 K per 10^6 years. Under these conditions, preexisting

organic compounds would have been destroyed and carbonaceous grains would have been converted to graphite. Indeed, these expectations are largely borne out: metamorphosed ordinary chondrites lack organic compounds but do contain graphite. Perhaps the most important outcome of internal metamorphisms in the parent bodies would have been the expulsion and delivery of volatiles through overlying layers to near-surface regions by diffusion or volcanic activity. Such outgassing or transport of fluids could have been accompanied by mineral-catalyzed synthesis of organic compounds.

Future Investigations

Little is known about how the physical structure and chemical composition of individual grains influence their growth under putative nebular conditions. To fill this knowledge gap, several types of investigations should be carried out. Calculations should be conducted to determine how the rates of formation or destruction of grain aggregates vary with particle hardness, porosity, and composition for metallic, silicate, organic, and icy grains. Theoretical studies should be complemented by laboratory experiments, some of which might be appropriate to carry out under microgravity conditions on the Space Station. From simulations of grain collisions under nebular conditions it should be possible to determine the relative "sticking efficiencies" of materials composed of the biogenic elements as compared with those of the rock-forming elements. The structures of aggregates produced in these investigations will provide useful models against which to compare grain aggregates obtained from meteorites, IDPs, and comets. For the experimental studies, facilities capable of accelerating small particles to a range of pertinent velocities would be very valuable.

Experiments should be conducted in which organic compounds and grains within inorganic matrices are subjected to laboratory simulations of phenomena presumed to have occurred on planetoids. For the biogenic compounds and phases used as starting materials in these experiments, modifications of physical, chemical, and isotopic properties as a function of environmental conditions must be determined.

Deeper understanding of the conditions of aqueous alteration, the identities of the precursor phases, and the nature of the resulting hydrous phases should be sought in petrographic and mineral-chemical studies of carbonaceous chondrites and IDPs. The fact that prebiotic compounds such as carboxylic acids and amino acids appear to occur only in these altered objects is particularly noteworthy, and elucidating the relationship between the origins of these inorganic and organic components is a research problem of high priority.

OBJECTIVE 5: *To determine the distribution, structure, and composition of presolar and nebular products in existing primitive materials in the solar system.*

Previous sections have considered, more or less chronologically, the evolution of chemical complexity in interstellar clouds, in the solar nebula that resulted from the collapse of such a cloud, and in solid objects that were formed in this nebula. Some end products of this evolution continue to exist today in asteroids, meteorites, comets, and IDPs and may be studied to elucidate this overall process.

ASTEROIDS

The asteroids are a large collection of small bodies that orbit the Sun, predominantly at distances of 2 to 3.5 AU in the "main belt" between Mars and Jupiter, residing in a transition region between the rocky terrestrial planets and the gas-rich outer planets. Dynamical calculations of asteroid orbits suggest that most of the asteroids have remained near their present relative positions in the solar system since their formation. Thus, one of the most important reasons for studying the asteroids is that they might preserve valuable information about the chemical and physical processes (e.g., condensation and accretion) operating in this transition region during the formation and early evolution of the solar system.

Our present knowledge of asteroids is based primarily on determination of their orbits and study of the temporal variability and spectral distribution of the reflected and emitted radiation from unresolved starlike images. Spectroscopic observations show that the asteroids vary in their surface mineralogical compositions and fall into broad classes that parallel, in a general fashion, some of the meteorite classes. The primitive nature of the bulk of asteroidal material is reflected by the predominance (by mass) of dark carbonaceous material (C-type asteroids) in the main belt.

Likewise, Ceres, which is the largest asteroid and contains approximately one-third of the total mass in the main belt, has a density of 2.6 ± 0.7 g/cm^3. This low density suggests that Ceres is far more volatile-rich than any of the terrestrial planets. Similar densities are in fact observed for the CI and CM2 types of carbonaceous chondrites; these meteorites are generally thought to be some of the most primitive early solar-system materials for which we have samples. The density of Ceres is also consistent with the predicted density of nebular condensates forming in the region of 300 K.

The study of primitive material in meteorites has provided valuable information about the chemical composition of the solar system and the chemical and physical processes operating in the solar nebula and early solar system. However, the enormous advantage in studying primitive asteroidal

materials is that the observed properties can be identified with a specific location in the solar system.

Future Investigations

Determination of the chemical composition of primitive asteroidal material with sufficient accuracy to make meaningful comparisons with the chemical composition of meteoritic material is of prime importance. If such a direct link can be made, then the large number of meteorite samples can be used as probes of the main belt region and of specific locations in the solar nebula. To this end the committee endorses the recommendation made by COMPLEX (Committee on Planetary and Lunar Exploration, *Strategy for the Exploration of Primitive Solar-System Bodies—Asteroids, Comets, and Meteoroids: 1980–1990,* SSB, 1980) that "the principal chemical elements present in asteroids to more than 1 percent abundance by atom be measured to an accuracy of about 0.5 atom percent. It is expected that these will include the elements H, C, O, Na, Al, Si, S, Ca, Ti, Fe, and Ni." The recommended measurement accuracies should be sufficient to permit informative comparisons with the known meteorite classes, to determine the oxidation state of major elements and to assess the degree of hydration of surface minerals.

Measurement of these elements should be made at one location on the surface at least; however, it is very desirable to make measurements at different locations to determine the scale and extent of surficial heterogeneity. Similarly it is also of interest to determine the scale and extent of radial heterogeneity by making measurements at depth or around craters where samples of the interior may have been exposed. Another important endeavor is determination of the bulk content and the chemical form of the major biogenic elements (H, C, N, O, P, and S). These may be present in a variety of molecular components that would be diagnostic of the primitive nature and degree of subsequent alteration of the asteroid. The distribution of carbon among various carbon-bearing volatiles (CO, CO_2, CH_4), carbonates, graphite, and organic polymers is of particular interest in these measurements.

A third area of investigation, which may take a longer time for implementation, is the measurement of the D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/^{16}O$, and $^{17}O/^{16}O$ isotopic ratios on at least one sample of an asteroid. The carbon isotopic ratios are of interest because of the carbonaceous nature of many asteroids and the observed variability of $^{13}C/^{12}C$ ratios in primitive meteorite components, whereas the oxygen isotopic ratios are important for comparison with the ratios in various meteorite classes.

Different types of scientific instrumentation and different means of investigation and research will have to be involved in these investigations.

Two useful techniques are X-ray fluorescence and gamma-ray spectroscopy. X rays are excited in surficial materials by solar radiation and provide information on the light elements (e.g., Mg, Al, and Si) in the topmost few micrometers of a surface. Gamma rays are emitted by long-lived natural radionuclides such as potassium, thorium, and uranium and also by shorter-lived nuclides formed by cosmic-ray and solar particle interactions with the surface. Both X and gamma rays can provide qualitative and semiquantitative analyses for a large number of elements.

Both nondestructive mapping techniques and destructive analytical techniques may be required to measure the abundances and chemical forms of the major biogenic elements. Spectral reflectance measurements in the ultraviolet, visible, and near-infrared region can be used to determine the mineralogy and composition of surficial materials and to map the spatial extent of different classes of materials (e.g., carbonaceous matter, hydrated phases). Thermal emission spectroscopy in the mid-range of the infrared region has similar applications. Because these two techniques are sensitive to different mineral phases present on the surface, they provide information complementary to the elemental analysis techniques, which are not sensitive to different phases.

Detailed characterization of the various molecular components in which the biogenic elements might be present will be considerably more difficult. Pyrolysis or combustion of carbonaceous material with analysis of the evolved vapors by gas chromatography/mass spectrometry has been used for meteorite samples and may also be used on a soft-lander. Morphological characterization of carbonaceous phases can be made by scanning electron microscopy; this would be possible on a returned sample or in situ by using a specially developed instrument for spaceflight.

Finally, the committee notes the suggestion that the Martian moons Phobos and Deimos may be captured asteroids, so their characterization is directly relevant to this objective.

METEORITES

Meteorites are interplanetary objects that survive passage through the terrestrial atmosphere as discrete bodies or associated fragments. Ranging in size from a few grams to several tons, meteorites are grouped into two broad categories, depending on whether they are undifferentiated or differentiated. The undifferentiated meteorites, or chondrites, have generally not been melted; consist of a mixture of small spheroidal objects (chondrules) and finer-grained, heterogeneous material (matrix); and have close resemblance in elemental abundances to the Sun. In fact, the nonvolatile elements are generally present in solar proportions, whereas the volatile ele-

ments are depleted to variable extents. The most primitive of the chondrites are the carbonaceous chondrites.

On the other hand, the differentiated meteorites, which include the irons, stony-irons, and chondrites, have been subjected to melting and fractionation events, do not consist of the simple chondrule-matrix duplex structure, and do not closely resemble the chemistry of the undifferentiated meteorites or the Sun. In many instances, the compositions of the differentiated meteorites (e.g., the chondrites) suggest chemical fractionations similar to those produced by igneous activity on the Earth and Moon. However, unlike the continuing igneous activity on the Earth, isotopic dating shows that most of the igneous fractionations reflected in the differentiated meteorites occurred 4.5 billion years ago, shortly after the formation of the solar system. Although the differentiated meteorites are important sources of information about the thermal histories of small planetesimals in the early solar system, they provide much less information than do the chondrites on presolar and nebular phases in primitive materials.

The carbonaceous chondrites, which are generally thought to be among the most primitive early solar-system materials for which samples exist, are the best candidates for preserving presolar and nebular phases or their signatures (e.g., "fossil" elemental abundance patterns or isotopic anomalies). Indeed, rubidium-strontium (Rb-Sr) dating of the CAIs in the allende carbonaceous chondrite has identified some of these inclusions as the oldest known solids in the solar system. The antiquity of the CAIs, and their resemblance (at least to a first approximation) to the chemistry and mineralogy of solid assemblages predicted as vapor-solid condensates at high temperatures from a solar composition gas, have led to intensive study of CAIs in the allende and other carbonaceous chondrites. However, to date no pristine nebular phases (i.e., vapor-solid condensates) have been identified unambiguously in any components of the chondritic meteorites.

A similar situation prevails in the search for presolar phases in primitive meteorites. The canonical model for the formation of the solar nebula envisioned a homogeneous, totally vaporized swirling cloud of gas that became a mixture of gas and dust upon cooling. In this scenario, a well-defined sequence of mineral phases, which became progressively more volatile-rich, formed from this homogeneous cloud with decreasing temperature. The end products of this sequence were postulated to be the oxidized iron- and H_2O-rich minerals observed in the carbonaceous chondrites.

However, the discovery of non-mass-dependent isotopic anomalies for oxygen and subsequently for titanium in CAIs showed that this viewpoint was fundamentally incorrect. A wide range of other non-mass-dependent and mass-dependent isotopic anomalies in refractory elements (Mg, Si, Ca, Cr, Ba, Nd, Sm) have since been observed in CAIs. Although the non-

mass-dependent isotopic anomalies have been interpreted in terms of material from different nucleosynthetic sources, no presolar grains have been unambiguously identified in the CAIs. Widespread isotopic anomalies are also observed in the biogenic elements hydrogen, carbon, and nitrogen and in the noble gases neon, krypton, and xenon.

The observed isotopic anomalies in the biogenic elements reinforce the notion from the refractory element isotopic anomalies that presolar material from a variety of environments was incorporated into chondritic meteorites relatively unaltered and without being thoroughly homogenized in the solar nebula. Large deuterium enrichments are observed in the insoluble organic matter that forms the bulk (70 to 80 percent) of all carbon in the CI and CM2 carbonaceous chondrites. These enrichments, which cannot plausibly be explained by mass fractionation in the solar nebula, are believed to indicate that these meteorites contain remnants of material from dark interstellar clouds. Isotopically heavy carbon found in CM2 chondrites may indicate the incorporation of carbon grains from red giant stars into these meteorites. Isotopically light nitrogen in components of the Allende meteorite may indicate incorporation of almost pure ^{14}N into this meteorite. At present, the complex picture described by the collective isotopic variations is incompletely understood but strongly suggests the preservation of presolar material from different nucleosynthetic sources and a variety of astrophysical environments.

Future Investigations

Observational studies of meteorites can be expected to continue to yield important results and to influence thinking on the chemical and physical processes responsible for shaping our solar system. In its 1980 report *Strategy for the Exploration of Primitive Solar-System Bodies—Asteroids, Comets, and Meteoroids: 1980–1990* (SSB, 1980), COMPLEX recommended that "a vigorous program of laboratory and theoretical investigations of meteorites be maintained" and also stated that "to realize the full promise of meteorite research it is necessary to maintain laboratory capabilities at the highest level of evolving technology and to encourage the development of even more sophisticated analytical methods." The committee endorses both these statements. In addition, a range of complementary studies should be pursued.

Some topics are exceedingly important. Laboratory studies are required of the molecular and isotopic compositions and yields of organic molecules produced by ion-molecule reactions, ultraviolet-pumped photochemical reactions, and high-temperature nucleation-condensation processes in a variety of astrophysical environments such as dark molecular clouds and cool stellar outflows. It is of utmost importance to conduct simulation experi-

ments under realistic conditions of pressure, temperature, composition, and energy flux or to perform the experiments in such a fashion as to permit meaningful extrapolations to these conditions.

Laboratory studies should also be made of the survivability of artificially induced and natural isotopic anomalies in refractory carbonaceous materials such as the insoluble organic polymer found in carbonaceous chondrites. Of particular interest is the change in a deuterium-enriched sample during heating in a solar composition gas for varying time periods. The resistance of ^{13}C-enriched graphitic grains to pyrolysis and isotopic exchange during heating in H_2-CO gas mixtures with solar $^{13}C/^{12}C$ ratios is also of interest. Such studies should be designed to provide kinetic data that can be applied to solar nebular models of the survivability of infalling interstellar grains.

Concerted observational studies of primitive meteorites should be made to determine unambiguously the nature, amount, and distribution of deuterium-enriched carrier phases. The use of in situ techniques such as the ion microprobe should be exploited fully in these efforts. Although the selective chemical dissolution techniques used in studies of noble gas and deuterium, ^{13}C, or ^{15}N carrier phases have provided invaluable information, these techniques are ultimately limited by their destructive nature, which renders observation of the carrier phases in the host meteorite impossible.

COMETS AND INTERPLANETARY DUST PARTICLES

Comets

Comets occupy a special place in the cosmic history of the biogenic elements and compounds: they hold promise of containing the most volatile-rich relics of processes that occurred in stars, interstellar clouds, and the protosolar nebula, while at the same time bearing evidence of their own formation and evolution as building blocks of planetary materials. Not only are they thought to contain grains and gas inherited from the interstellar cloud that spawned the solar system, they are also expected to have accreted both refractory and volatile material formed in cold regions of the protosolar nebula. In addition, a role as carriers of volatile and biogenic elements to the terrestrial planets where, at least on Earth, life arose and evolved is attributed to them.

These expectations arise from theories that comets formed by cold accretion of interstellar dust and gas or solar nebular condensates, or mixtures of these materials, into small planetesimals whose size, composition, and orbital distance from the Sun precluded subsequent differentiation. In turn, the theories are based on estimates of the relative abundances of the major elements in comets as inferred from a long history of ground-based and airborne observations of species in their comae and tails and from in situ

studies of Comet Halley. The relatively high ratio of volatile (e.g., water) to involatile (e.g., silicates) substances observed in comets signifies that they were accreted at great distances from the Sun and then never heated for long to temperatures much above the sublimation point of water ice in space. Although resembling primitive carbonaceous chondrites in exhibiting approximately solar atomic ratios of the metallic elements, comets more closely approximate the Sun and interstellar frost in the relative abundances of the volatile elements. These abundances, coupled with the putative lack of internal differentiation, place comets among the most primitive solid objects in the solar system and the likeliest to have preserved intact the gases and grains that accreted to form them. For these reasons, *comets assume the highest priority among solar-system objects for study of the cosmic evolution of compounds and phases containing the biogenic elements.*

Many major scientific questions can be addressed by the study of comets. These questions should be kept in mind during present and future investigations. They include the following: possible relationships among biogenic compounds and phases in cometary, meteoritic, and interstellar matter; similarities between cometary and interstellar organic chemistry; and the insertion into, and stability of, interstellar material in cometary nuclei.

Prior to the return of Comet Halley, the nucleus of a comet had never been directly observed, and inferences about its composition relied on reconstructions based on the abundances of radicals, ions, and atoms observed in the coma and tail. Reconstructions of unobservable "parent" molecules in the nucleus from observable "daughter" species are fraught with uncertainties. Nonetheless, H_2O and HCN had previously been identified as parent molecules.

Exciting new data pertinent to the gas phase have been obtained from Comet Halley by the Giotto and Vega spacecraft, as well as from related ground-based and airborne observations. Some of these new findings point to CO, CO_2, and perhaps H_2CO as additional parent molecules. In particular, the gases released from the nucleus were composed of about 80 percent water, 10 to 20 percent CO, a few percent CO_2, and smaller amounts of other gases. In addition, analyses of the coma gas phase by neutral and ion mass spectrometers revealed a surprising abundance of peaks attributable to hydrocarbons and other organic compounds. Although the identities of these compounds are presently controversial, their occurrence strongly underscores the complexity of the organic chemical content of comets. Other especially noteworthy findings were the discovery of jets of cyanide associated with the emission of dust from active regions of the nucleus and the observation that the source of much of the CO was extended in the coma. This raises the novel possibility that the dust may contribute species directly to the gas phase.

Perhaps the most significant and exciting new insights into comets arose from direct observations of the nucleus of Comet Halley and its solid dust component. Fine-grained dust composed of dark, apparently carbonaceous, matter was found covering inactive regions of the comet surface and ejected in plumes from active regions into the coma. Spacecraft analyses of dust grains in the coma by impact mass spectrometry revealed a variety of compositional types. In addition to silicatelike particles and inorganic grains of chondritic composition, several populations were found to be composed of various combinations of the biogenic elements carbon, hydrogen, oxygen, and nitrogen exclusively, as well as mixed with inorganic elements. The size and composition of the particles are consistent with our knowledge of interstellar dust, but no conclusions can yet be drawn about their origin. Clearly these particles and their counterparts or analogues in meteorites and IDPs provide fascinating new targets for study.

In principle, the isotopic composition of hydrogen, carbon, nitrogen, sulfur, and other elements in comets could provide clues to their origin. Isotopic measurements obtained at Comet Halley for carbon, nitrogen, and sulfur, although still imprecise, appear to fall within the range of solar-system materials. Similarly, the bulk ratio of deuterium to hydrogen is compatible with that of terrestrial materials and bulk meteorites. A detailed study of dust at Comet Halley to probe the possible existence of inclusions with large D/H ratios was not possible.

Interplanetary Dust Particles

Interplanetary dust particles (IDPs) are extraterrestrial particles, typically less than 1 mm in diameter, that survive entry into the upper atmosphere and are currently collected by high-flying aircraft. Their contents of solar wind noble gases and cosmic-ray tracks attest to their extraterrestrial origin. Among the variety of particle types that have been identified, the most common ones exhibit the solar pattern of relative abundances for major and minor elements that typifies primitive, chemically unfractionated, chondritic materials. Often called "cosmic dust," these IDPs constitute a unique collection of samples that complement meteorites as "fossils" of the earliest history of the solar system. Some may be of interstellar origin, but the bulk are presumably cometary or asteroidal.

Most of the chondritic particles that have been examined are in the 5- to 50-μm size range. They are typically black, and semiquantitative analyses show them to contain 2 to 5 weight percent, or higher, of carbon. Abundances of hydrogen and nitrogen have not yet been measured. Two populations make up these particles: one contains only anhydrous phases; the other is composed largely of hydrated minerals, among which the most abundant are layer lattice silicates (clays).

The anhydrous particles are unique in several distinctive ways. They contain much larger amounts of carbon than comparably anhydrous meteorite samples. Their extreme porosity suggests previous filling by ice and structural fragility, the latter being consistent with physical properties of materials in cometary meteors. They are composed of extremely small grains, ranging from micrometers down to tens of angstroms in size, assembled in a highly porous, three-dimensional structure. Especially noteworthy among the minerals found as grains are carbides, graphite, and sulfides, along with olivine and enstatite.

Carbonaceous material appears to be ubiquitous as amorphous coatings and clumps and as a medium for the embedment of other inorganic grains. The lack of any counterpart for materials with these characteristics in the meteorite collections argues strongly for a different, probably cometary, origin.

Recent measurements performed on individual IDPs with the ion microprobe revealed anomalously high D/H ratios associated with organic carbonaceous material. Similar findings were obtained on both anhydrous and hydrous IDPs. In the case of carbonaceous chondrites, such high ratios have been interpreted as indicating the presence of interstellar organic matter. The commonality of this organic matter among several types of primitive materials may reflect a common interstellar source.

Some of the IDPs composed of hydrous phases may also be related to comets. Although the clay minerals in some cases closely resemble those of carbonaceous chondrites, in other cases they are distinctly different. The degree of compactness exhibited by these particles may reflect the influence of liquid water on the origin of the hydrous phases. If such were the case, and if the particles were determined to be cometary based on other criteria, the implications for cometary thermal evolution, physical properties, and solution-phase organic chemistry would be far-reaching.

Future Investigations

For the foreseeable future, IDPs will provide the only prospect for direct study of comet samples. Therefore, a vigorous program of ground-based studies should be pursued to characterize them according to physical properties and chemical, isotopic, and mineralogical composition, with primary emphasis on the phases and structures containing the biogenic elements. Furthermore, to expand the size of the existing inventory and perhaps obtain particles not captured in the stratosphere, opportunities should be exploited to collect IDPs in relatively unaltered form in low Earth orbit, as for example on the Space Station.

The so-called primitive IDPs appear to have no analogues in the meteorite collections and, therefore, are most likely to be cometary in origin. In

contrast, those "chondritic" particles that contain layer lattice silicates grossly resemble samples of carbonaceous chondrites whose chemistry and mineralogy have been altered by liquid water, but the detailed similarities that would confirm a meteoritic rather than a cometary origin remain to be established. For this reason, the latter particles must be included along with the "primitive" ones in future investigations, and parallel studies at very high spatial resolution of the finest-grained material in carbonaceous and unequilibrated ordinary chondrites must be exploited to establish the necessary comparative data base.

For comets, an approach is needed to address—via in situ investigations—scientific questions about the elemental, isotopic, molecular, and mineral composition of the comet nucleus, as well as its physical properties and geological characteristics. Included in any mission package should be instruments designed to determine (1) the identities and abundances of the volatile organic compounds at depth in the nucleus as well as in the gas and dust of the coma, (2) the physical structure of the coma dust, (3) the abundances of the biogenic elements in the dust, and (4) the isotopic compositions of the biogenic elements in the gas phase. The proposed Comet Rendezvous Asteroid Flyby (CRAF) mission would provide such an instrumental complement and would thus be the next major advance in our scientific understanding of comets. Furthermore, this mission would serve as a necessary precursor to a comet nucleus sample return mission *(Strategy for the Exploration of Primitive Solar-System Bodies—Asteroids, Comets, and Meteoroids: 1980–1990,* SSB, 1980; *A Strategy for Exploration of the Outer Planets: 1986–1996,* SSB, 1986b).

Over this same time frame, returning short-period comets and new comets will provide occasions for ground-based and airborne observations. These opportunities should be exploited to address new questions raised by the recent studies of Comet Halley.

For the longer term, however, highest priority for the study of the cosmic evolution of the biogenic compounds and phases must be given to the return of a comet nucleus sample. Under carefully controlled laboratory conditions, the full range of state-of-the-art analytical instruments and techniques could be brought to bear. Perhaps most important, the ingenuity of an international community of scientists would be released from the constraints of preprogrammed experimental approaches imposed by the requirements of remote analyses. With the expectation that such a sample will be available some time near the turn of the century, it is timely now to begin developing the analytical and sample manipulation techniques required to operate at subambient temperatures on a micrometer scale on samples likely to be dominated by ices and volatile components. The committee strongly endorses the recommendation for a comet sample return mission in *Space Science in the Twenty-First Century* (SSB, 1988a,b).

3
Early Planetary Environments: Implications for Chemical Evolution and the Origin of Life

INTRODUCTION

Life originates and evolves on planets. Depending on the location with respect to its central star, the endowment of elements and energy sources, and the evolutionary path taken by a particular planet, the surface environments may become either hospitable or inimical to the origin of life. The comparative study of planets then is essential to understanding the relationship between planetary development and the origin and evolution of living systems.

As a minimum for life to arise and evolve on a planet, the persistence of liquid water and a hydrologic cycle operating in concert with geochemical cycles of the biogenic elements would appear to be required. Physical processes occurring in surface environments also had to sustain the chemical synthesis of structures that would become capable of metabolism and self-replication. The central role of organic chemistry in life on Earth underscores the importance of understanding how processes operating initially in an essentially inorganic realm could have led eventually to the organic structures that are now recognized as life.

In a more general context, the organic chemistry of planetary environments is an extension of the cosmic evolution of the biogenic elements (see Chapter 2) into the planetary epoch. Knowledge of the processes that produce organic matter, wherever it occurs in the solar system, is central to our understanding of chemical evolution.

The planetary bodies and satellites in the outer solar system are of primary interest in this context because they are natural laboratories in which the chemical evolution of organic matter can be studied directly. Investigation of their present state can yield insight into the complexity of organic

chemistry that can be attained in the outer reaches of the solar system. A variety of environments exist within which these experiments are taking place today. The occurrence of selective pathways for the synthesis of organic compounds related to abiotic processes on the primitive Earth can also be investigated by studying the processes and products found in these environments. Furthermore, it may be possible to determine the relationships among the materials in asteroids, the satellites and planetary rings of the outer solar system, and the components of primitive meteorites and comets. There has been speculation about the possible existence of living organisms in Jupiter's atmosphere and also about a hypothetical ocean that could provide an environment for life beneath the ice cover of Europa. Both notions suffer from serious theoretical objections.

The life histories of the terrestrial planets Earth, Mars, Venus, and Mercury and of the solid satellites, Moon and Io, underscore the relationship between planetary processes and the origin of biological processes. These histories may be compared in terms of hypothetical stages in the life of such planets, as indicated in Figure 3.1. For example, Earth passed through to the stage of plate tectonism; core formation and accretion played major roles in determining its early thermal history and constraining the time of origin and the conditions of the early milieux of atmosphere, ocean, and crust in which living systems arose; and plate tectonism maintains the bio-

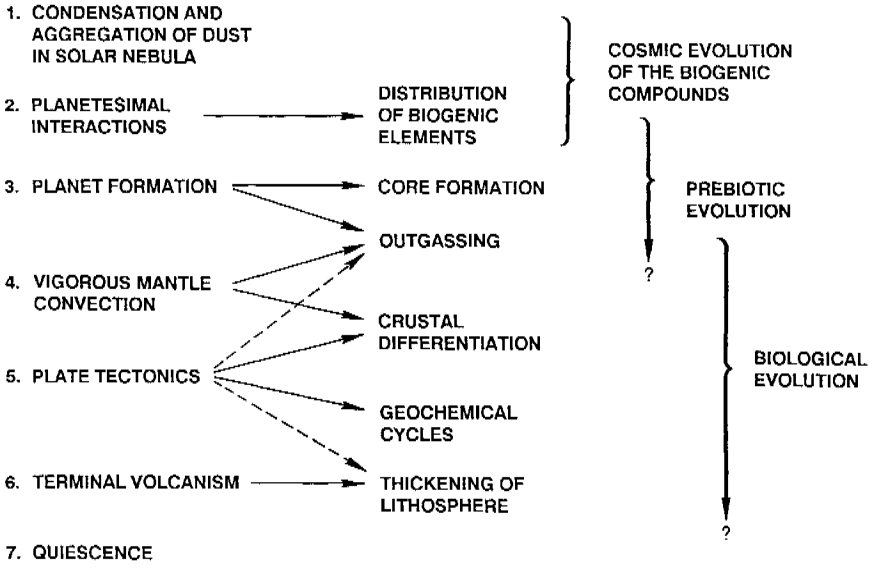

FIGURE 3.1 Stages of planetary evolution (after Kaula, 1975).

geochemical cycles essential for its global ecosystem. A planet may not progress through all stages in Figure 3.1, depending on these same factors. For instance, the Moon and Mercury appear not to have gone beyond core formation. Mars does not show convincing evidence of plate tectonics at any time in its history. Venus may have slow plate tectonics. Io has intense volcanism. The causes of divergences in development among the terrestrial planets have to be understood because they provide bounds on any general theory relating the origin of life to the origin and evolution of planets. Two major goals can thus be formulated for studies on early planetary environments that are crucial to our understanding of organic chemical evolution and the origin of life.

GOAL 1: *To understand the processes responsible for the chemical evolution of organic matter in the outer solar system.*

GOAL 2: *To understand how the conditions for chemical evolution and the origin of life were influenced by the physical and chemical development of the terrestrial planets.*

THE OUTER PLANETS

OBJECTIVE 1: *To determine the origin and distribution of organic matter and disequilibrium products containing the biogenic elements in the hydrogen-rich atmospheres of the outer planets.*

The giant planets—Jupiter, Saturn, Uranus, and Neptune—are composed of large amounts of gas. The icy bodies of the solar system, the outer satellites of Jupiter, the satellites of the other giant planets, and Pluto—all have substantial amounts of ice and variable amounts of silicate and iron in their interiors. According to one current theory, formation of planets in the outer solar system began with the aggregation of ice-rich grains from the solar nebula into cometlike planetesimals (see Chapter 2) followed by accretion of the small bodies into Earth-sized planetary cores. The accretion process generated secondary atmospheres around the cores as these grew in size and mass. These cores then acquired thick gaseous envelopes by gravitational attraction of surrounding nebular gas. The moons of the giant planets presumably accreted in similar fashion but with differing proportions of ice and silicate and without accumulation of nebular gas.

Astronomical observations of Jupiter, Saturn, and their moons have been made from Earth and by the two Voyager spacecraft. Both Jupiter and Saturn have atmospheres that are enriched in carbon and nitrogen with respect to the solar values, by factors of about two and three, respectively, whereas oxygen appears to be deficient in Jupiter's atmosphere for reasons

that are not yet understood. Hydrogen is, of course, the dominant constituent of both atmospheres and the major constituent of Uranus and Neptune as well. The atmospheres of these smaller giant planets are less well understood, but it is apparent that carbon, at least, is even more enriched on Uranus and Neptune than on Jupiter. This enrichment is most likely a result of degassing of the cores during accretion.

Chemistry in these atmospheres is limited by the extreme overabundance of hydrogen; by the absence of a long-lived solid surface on which material could collect, become concentrated, and undergo further chemical reactions; and by the increase in temperature with depth that, along with atmospheric convection, will lead to the breakdown of compounds produced photochemically at higher altitudes either in the gas phase or on grain surfaces. Nevertheless, some nonequilibrium chemistry is certainly expected in these atmospheres as a result of energy supplied externally from above (solar ultraviolet light; bombardment by electrons, protons, cosmic rays), reactions driven by lightning discharges, and the effects of convection in the atmospheres themselves, which can bring species formed in one thermal regime into another where they will be out of equilibrium. Indeed evidence of these processes is available in the form of ethane and acetylene, formed from methane in the upper atmospheres of these planets; as yet unidentified colored material in atmospheric clouds and hazes; and constituents such as phosphine, germane, and possibly CO that have been formed at low elevations and brought up to visible levels by vertical currents.

All of these products and processes are worthy of additional study for what they can tell us about the origin of organic material in hydrogen-rich environments. Some regions in these planetary atmospheres may resemble conditions in the primitive solar nebula, which in turn were probably representative of a large class of cosmically abundant environments. Hence understanding these chemistries—what drives them, what they produce—is of considerable interest for attempts to constrain possible starting conditions in the early solar system.

OBJECTIVE 2: *To elucidate the organic chemistry and the origin of carbon oxides on Titan.*

The complexity that can be achieved in the organic chemistry of a *small* planet with a strongly reducing atmosphere holds perhaps even greater interest than the giant planets. In this context, "small" means a body whose mass is meager enough to allow hydrogen to escape easily from its atmosphere. This is one of the distinguishing characteristics of the Earth and the other inner planets. It also applies to the satellite of Saturn, Titan, whose present atmospheric composition has been thought to resemble the highly reducing end member in the spectrum of possible models of the primitive Earth atmosphere. This satellite has a solid surface that is at a low tempera-

ture, thereby avoiding the other two factors limiting organic chemical evolution on the giant planets. The problem is that the temperature of Titan's surface is so low—94 K—that liquid water is out of the question. Liquid ethane, however, may exist dimly illuminated by light from the distant Sun that filters through dense, ubiquitous layers of smog.

Much interesting chemistry is indeed taking place on Titan. The atmosphere exerts a surface pressure of 1.5 bars, consisting primarily of nitrogen with 1 to 6 percent methane. Ten to 15 percent argon may also be present: the current uncertainty in the mean molecular weight would permit it (direct detection is very difficult), and arguments based on cosmic abundances and the trapping of gases by water ice (clathrates) support this possibility.

Of greatest interest are the trace gases shown in Table 3.1. Here are some of the results of spontaneous chemical reactions in a reducing atmosphere. Not only are hydrocarbons and nitriles present, both CO_2 and CO are also present.

The first two classes of compounds are expected in such an atmosphere as a result of reactions between fragments of nitrogen and methane. This chemistry is driven primarily by precipitating electrons from Saturn's magnetosphere, but there are also contributions from solar ultraviolet photons

TABLE 3.1 Composition of Titan's Atmosphere

Species	Name	Abundance
Major Components		
N_2	Nitrogen	73–99%
Ar	Argon	10–15%
CH_4	Methane	1–6%
H_2	Hydrogen	0.1–0.4%
Hydrocarbons		
C_2H_6	Ethane	20 ppm
C_3H_8	Propane	20–50 ppm
C_2H_2	Acetylene	2 ppm
C_2H_4	Ethylene	400 ppb
C_4H_2	Diacetylene	30 ppb
CH_3C_2H	Methylacetylene	30 ppb
Nitriles		
HCN	Hydrogen cyanide	20 ppb
HC_2CN	Cyanoacetylene	10–1000 ppb
C_2N_2	Cyanogen	10–100 ppb
Oxygen Compounds		
CO_2	Carbon dioxide	10 ppb
CO	Carbon monoxide	60 ppm

and cosmic rays. Presumably these atmospheric reactions also give rise to the ubiquitous haze layer of organic matter, which almost certainly consists of condensed simple organic compounds and photopolymers. If over geologic time ethane were produced as a by-product of methane decomposition in the upper atmosphere, it could accumulate into liquid bodies on Titan's surface.

What is the source of oxygen for the two oxides? Given the low surface temperature, water vapor can be excluded from the ices on Titan's surface. Water from the outside, in the form of infalling meteorites or icy debris from the Saturn system, is a good possibility. Another source would be primordial CO along with CH_4, trapped in the ices that formed Titan.

Titan offers us a very interesting natural laboratory for testing ideas about chemical evolution in reducing atmospheres. The gases listed in Table 3.1 can only be a subset of the total constituents to be found. The smog itself is likely to contain more complex substances than those listed in the table, which formed as a result of polymerization in the atmosphere. This material, as well as the condensable forms of the species given in Table 3.1, will settle on Titan's surface, sinking or dissolving in the seas of ethane or accumulating in drifts on icy outcrops.

It would be of great interest to determine the level of chemical complexity achieved in this natural environment. Is there evidence of any preferred pathway? Are unlikely reactions catalyzed in some unforeseen way? Are compounds of biological interest, such as amino acids or adenine, produced? Are any of these results relevant to the events that preceded the origin of life on Earth? A beginning for answering these and other related questions could be provided by the NASA-ESA (European Space Agency) Titan Cassini mission, currently under study, because extensive chemical analysis of the atmosphere and some surface science are being considered for inclusion in its instrument package.

OBJECTIVE 3: *To characterize the organic matter on the dark surfaces of the asteroids, satellites, and planetary rings of the outer solar system.*

Atmospheres are not the only locales for organic chemistry in the outer solar system. The dark surfaces of Phoebe, the leading hemisphere of Iapetus, the satellites and rings of Uranus, and comet nuclei all seem to require the presence of carbon compounds, but not necessarily the same compounds. The dark coatings found in the Uranus system seem distinctly more neutral in tint than those found on Iapetus and Phoebe, which absorb more in the blue than the red. Phoebe and the dark side of Iapetus do not match either. Were these coatings formed by physical processes acting on the surfaces, or were they formed elsewhere and accreted along with other components at the time these various objects formed? What is their rela-

tionship to the coatings on comet nuclei, which in the case of Halley has a reflectivity of about 3 percent? What is this dark material? The organic residue from the Murchison meteorite provides a reasonably good spectral match to Iapetus (but not Phoebe).

In addition to the dark dust revealed by the Halley encounter, radicals such as C_3, CH_2, C_2, and CN, seen in comet spectra for years, indicate the presence of organic "parent molecules" trapped in or on the ices of the nucleus. Surprisingly, CO_2 was identified as a parent molecule in the Halley nucleus. Its source remains controversial, but attempts to find evidence of solid CO_2 in the outer solar system seem worthwhile. Can cometary ices accumulated in the solar nebula have supplied the building blocks for the asteroids, satellites, and planetary rings of the outer solar system?

We have come full circle and, once again, are considering conditions that existed in the primitive solar nebula and may have afforded the components accreted into bodies of the outer solar system, some of which could even have originated in the interstellar medium before the nebula formed. These conditions should be understood not only because of their intrinsic interest; incorporated in comets and meteorites, the components must have been brought to the primitive Earth. Hence, the proportions of the biogenic elements and the nature of the compounds they formed, wherever they may be found in the current epoch, are of considerable importance to understanding the chemical evolution of organic matter that led to the origin of life.

THE TERRESTRIAL PLANETS

Like all the terrestrial planets, the two discussed here—Earth and Mars—are composed mainly of silicates and iron and contain only trace to minor amounts of the volatiles and the biogenic elements that are necessary for life. Historically, two scenarios have been proposed to explain the extreme depletion of the terrestrial planets in gases and volatile compounds. (1) The planets originally condensed as giant gaseous, protoplanets, and the volatile material was subsequently lost, possibly by action of the solar wind. (2) The solid material that formed the planets condensed from or partially equilibrated with the solar nebula at high temperatures and then accreted into rocky planets. The first scenario involves difficulties in getting rid of gas against the gravity of the planet and has not been widely accepted. The mechanics and chemistry of the accretion of planets from planetesimals have been studied extensively and are discussed below.

Condensation or equilibration at a single temperature cannot explain the composition of Earth, however. The Earth is strongly depleted in rock-forming elements as volatile as potassium and may be depleted somewhat in silicon relative to magnesium. This would imply quantitative depletion of

the biogenic elements hydrogen, carbon, and nitrogen, which are obviously present as H_2O, CO_2, and N_2 and are bound in minerals at the surface and which may be present in the core. Analogous situations hold true for Mars and Venus. The conclusion that condensation is not the whole story is supported by the fact that even individual primitive meteorites (see Chapter 2) consist of mixtures of minerals and inclusions that require a wide range of condensation temperatures. Mixing of volatile-rich and nonvolatile materials on the respective bodies must have occurred to account for the compositions of Earth, Mars, and Venus, as well as for these meteorites. The endowments of biogenic elements in volatile-rich bodies (e.g., comets and asteroids) supplied to the terrestrial planets were prerequisites for the origin of life, yet their origin and delivery were the results of astrophysical processes operating elsewhere in the solar system.

Earth

Accretion by Impacts

According to the scenario described earlier, the terrestrial planets grew as a result of larger planetesimals capturing smaller ones by gravitational attraction and collision. During this process, near misses among the bodies tended to perturb their orbits so that the approach velocities were a fraction of the escape velocity of the largest planetesimal in an orbital zone of accretion. Once the Earth and Venus had grown to a significant fraction of their final size, orbits were strongly perturbed and the planetesimals remaining in the inner solar system were mixed. Accretion models typically yield a virtually fully formed Earth in 10^7 to 10^8 years.

Such accretion, however, has important implications for the timing of the development of environmental conditions suitable for the origin of life, which is discussed in more detail below. Model calculations indicate that several lunar- (0.01 Earth mass) to Mars-sized (0.1 Earth mass) objects would have impacted the Earth. The number, size, and position of the terrestrial planets are partly a consequence of the randomness associated with the small number of these bodies. Indeed, the Moon is believed by some to have been formed by a very large impact with the Earth. The conditions associated with a very large impactor of lunar or Martian size are extreme and would have wiped out much of the earlier structure of the planet to a depth of many kilometers, with concomitant loading of the atmosphere with hot rock vapor. Any life forms that may have existed at the time would not have survived.

The rate of impact of numerous smaller objects would have affected the amount of volatiles retained in the Earth's atmosphere. This process can be visualized by comparing the energy fluxes per unit area with the present

heat flux supplied by the Sun, 1340 W/m^2, and the current heat flux from the interior of the Earth, 0.08 W/m^2. Sustained heat fluxes much larger than the solar flux would have heated the atmosphere, so that liquid water could not have existed. Fluxes larger than the interior heat flux would have afforded significant geological effects. For example, accretion of the Earth in 10 million years would correspond to a heat flux of about 4000 W/m^2, which may have been enough to form a massive water greenhouse with molten rock at the surface. Late in the accretion, especially after the last major impact, the energy fluxes were likely to have been much lower, and water greenhouse atmospheres could exist only after fairly large impacts.

The size distribution and the flux of the objects that formed the Earth in the first 10^8 years are thus important. With a continual flux of smaller objects, water would have been kept in the atmosphere and hydrogen would have been lost to space at a significant rate. The water that dissolved in molten rock would have been transported to the interior by convection. Below about 100 km depth, the water would have been lost by reaction with metallic iron to form iron hydride in solution in the iron phase and ferrous oxide in the silicates. Carbon as CO, CO_2, or CH_4 is not readily lost to space, but carbon is soluble in iron and some should have entered the core. In these regards the case of very large impacts has not been modeled. Would a very large impact into an existing atmosphere and hydrosphere have ejected a portion into space and injected another into the upper mantle? How much rock vapor would have been produced and what influence should it have exerted on the resulting composition of the gases in the atmosphere? How long would it take to cool the surface sufficiently to allow liquid water to form again? More studies of the size distribution of impacting bodies and the effects of very large impacts are needed to address these questions.

OBJECTIVE 1: *To determine when and how the volatile elements necessary for life were added to the surface regions of the Earth.*

In the solar nebular region where the silicate- and metal-containing building block for Earth condensed, the temperatures were unfavorable for retaining water and other volatiles, as noted above. Thus, it has been proposed that volatile elements were supplied by impacts of icy or volatile-rich rocky objects that accreted in the outer solar system. These objects were scattered into the inner solar system, as well as farther from the Sun, by gravitational perturbations resulting from formation of the giant planets. The remnants of these icy bodies exist today as comets, but they visit the inner solar system infrequently. Some theoretical modeling of the process of comet accretion in the solar nebula has been done, and these models suggest that a maximum size between 10 and 100 km could exist under some boundary conditions. In this case, comets are not likely to have been the projectiles for major impacts. However, Pluto's icy satellite, Charon, is

0.06 times the diameter of Earth, has about the mass of the Earth's oceans, and may represent the largest end member of the comet size distribution. The expected total supply of material by comets to the Earth during and after accretion is poorly constrained. Direct observation of the maximum size of comets, although very difficult, is highly desirable.

Even if comets were the major source of volatiles, it is not clear whether they would have supplied much complex organic matter to the Earth. Large objects impacting Earth at cometary velocities are expected to vaporize completely, and the survival of organic compounds under such conditions would appear problematic. Small meteorites derived from asteroidal parent bodies can pass through the atmosphere without significant heating of their interiors. The bulk of the incoming mass, however, is in much larger but infrequent projectiles, whose high-velocity impacts with the Earth should also lead to vaporization. For large cometary and asteroidal objects, it would be of considerable interest to know the composition of the resulting vapor clouds. Studies should be carried out to determine the bounds on the input of intact cometary and asteroidal organic compounds to chemical evolution.

Tectonics and the Development of Earth's Early Atmosphere and Hydrosphere

The timing of the last lunar- or Martian-sized impact is unknown; it could have been as early as 4.5 billion years ago, the age of the oldest Moon rocks. The origin of an atmosphere and an ocean following the last major impact was probably rapid, but quantitative observations exist only for radiogenic rare gases. The massive water atmosphere would have condensed into oceans more or less the present size, leaving behind a thick atmosphere containing the noble gases as well as hydrogen-, carbon-, nitrogen-, and sulfur-bearing species. What was the composition of that atmosphere?

Accretion and the formation of the Earth's core are now thought to have occurred simultaneously. Giant impacts supplied their already differentiated cores to the Earth. Enormous amounts of heat were added to the Earth by these processes. Most of this heat had to escape to space for the Earth to cool below the melting point. That is, the heat flux from the Earth's interior during the first 100 years was probably greater than all the heat flux since. Plate tectonics (or any similar broad convective overturn) is much too slow to release this heat. For example, a heat flow 100 times the present one would require 10,000 times the current rate of plate motions or subduction of the 10,000-year-old lithosphere. The time is much too short for the more dense oceanic mantle to begin cooling. A more likely form of convection is by total melting of material at depth and eruption of the

material to the surface. Such silicate melts have extremely low viscosities and spread out in thin flows that cool rapidly. For example, the eruption rate of 20 mm per year necessary to supply 6 W/m^2 is obtained by noting that the heat content of such flows is about 3 MJ/kg. This rate would recycle the mantle in 150 million years, a duration compatible with the probable time interval.

Implicit in the idea of early core formation and mantle melting is that preexisting metallic iron carried in by accreting bodies would have been removed from near-surface regions. If segregation of iron into the core was inefficient and metal remained in the upper mantle to buffer the redox state of magmas, or if the metallic core, mantle, and outgassed volatiles were all in thermodynamic equilibrium during the period of rapid heat loss, CO and CH_4 would have been the predominant thermodynamically stable forms of carbon injected into the atmosphere from the interior. The primitive atmosphere (highly reduced) would have been rich in H_2, CO, CH_4, NH_3, and H_2S (hydrogen sulfide). Furthermore, the impacts of large iron-bearing asteroids comparable in mass to that of the oceans may have yielded pulses of highly reduced gases as a result of equilibration between vaporized iron and elemental hydrogen, carbon, nitrogen, and sulfur.

In the absence of metal, the composition of the atmosphere would have been determined by the redox state of the near-surface metal-free silicate melts. Under this circumstance (neutral redox composition), CO_2 would have been the predominant carbon-bearing gas; other major atmospheric constituents would have been N_2 and H_2O; sulfur would have emerged from hydrothermal vents as H_2S; and CH_4, CO, and H_2 would have occurred in trace amounts at best.

Synthesis of organic compounds for chemical evolution would have occurred more readily under highly reduced conditions (see Chapter 4); however, there is no direct evidence bearing on the composition of Earth's earliest atmosphere. A better understanding of the geophysical and geochemical history of metallic iron in the upper mantle during tectonic evolution is required. Such understanding may be gained by further study of Archean mantle-derived rocks, upper mantle xenoliths, lunar basalts, and igneous rocks from Mars, including the so-called SNC (Shergotite, Nakhlite, and Chassignite) meteorites of putative Martian origin.

Although no direct evidence exists concerning the relative abundances of CO_2, CO, and CH_4 in Earth's earliest atmosphere, modeling of atmospheric photochemical processes indicates lifetimes of the order of tens of years for a primordial endowment of CH_4, and steady-state sources for this gas are problematic in the absence of metallic iron (projectiles may have supplied some metallic iron). Until further insight into the primitive atmospheric composition emerges, the assumption that it was highly reducing cannot be

taken for granted, and pathways for organic synthesis starting from CO_2 should be explored (see Chapter 4). Also, a sedimentary rock column, brought back from Mars as a documented core, could provide direct information about the early evolution of that planet's atmosphere, which must have paralleled our own.

As at present, competing processes would have tended to both degas volatiles and return them to the Earth's interior. Lavas from total melting at depth were probably hot enough and had a low enough viscosity to lose most of their volatiles even beneath the ocean. Once cooled at the surface, olivine-rich glass would have tended to react with H_2 and CO_2 to form hydrous minerals and carbonates. Stirring of the surface by impacts would have aided penetration of water into warm rock, as well as hydration and carbonation reactions. The latter reactions would have begun to remove CO_2 from the early massive atmosphere. What was the size of the atmosphere during this early stage of tectonism?

If a substantial fraction of the carbon presently tied up in carbonate minerals was originally in the atmosphere as CO_2 after accretion, a massive CO_2 atmosphere of the order of several tens of bars could have existed. The greenhouse effect associated with this atmosphere would have countered the glacial temperatures inferred to have been the consequence of the lower luminosity of the early Sun; CO_2 dissolved in the water would have precipitated $CaCO_3$ at the moderate temperatures of the marine (shallow) hydrothermal circulation system. If this mechanism for removal of CO_2 from the atmosphere was not supplemented by its weathering counterpart on land (as happens today) because land surface was lacking, a thick CO_2 atmosphere and warm surface temperatures (<100°C) could have persisted into the Archean. The implications of such an atmosphere for the geochemistry of seawater and prebiotic chemical evolution should be investigated.

Once the last pockets of very hot material in the mantle erupted and cooled, some form of plate tectonics became the dominant mode of heat transfer from the Earth's interior. With the onset of plate movements resembling today's, volcanic activity and metamorphism released gases, and lower-temperature alteration returned volatiles into the interior—particularly at midoceanic ridges. Although the rates of the processes were probably enhanced by the higher temperature of the Earth's interior, and perhaps by greater global rates of plate tectonics, it is unclear whether there was a net gain or loss of near surface volatiles during this epoch. If the redox state of the magmas during this stage of tectonic development was similar to that recorded in the geological record from the present back to 3.8 billion years, N_2, CO_2 and H_2O would have been the dominant gases in the atmosphere. It is unknown at what time such a tectonic regime took hold, but the evidence suggests possibly earlier than 3.8 billion years ago (see below).

OBJECTIVE 2: *To constrain the conditions on the early Earth for determining the timing and probable environments for the origin and maintenance of the first organism.*

Because a fundamental characteristic of all life is to be far from equilibrium with its surroundings, geophysically active boundary regions that are also far from equilibrium would appear to be particularly interesting environments for the origin of life. These regions would have included fumaroles and volcanic vents on continents and continental shelves, deep-sea plate spreading centers, island-arc volcanic vents, the land-air interface, the sea-air interface, and especially the sea-land-air interface. The geophysics and geochemistry of these environments warrant careful study to determine their potentiality as sites not only for producing organic molecules, but also for producing self-organizing structures as precursors of self-replicating systems (see Chapter 4).

The aspects of plate tectonics that do not involve continents, including midoceanic ridges with hydrothermal vents, oceanic islands, and island arcs, probably existed as early as did liquid water and tectonism, but there is little hard evidence for this. The origin of continents is more poorly understood, and the best estimates of continental growth and recycling come from geological data. The earliest (3.8 billion years old) preserved rocks from Greenland resemble those from active continental and island-arc regions. Detrital zircons in ancient sediments indicate continental or island-arc environments as early as 4.1 billion years ago.

It is especially noteworthy that the Earth's microbial ecosystems revealed in 3.5-billion-year-old sediments from Western Australia appear to have occupied shallow marine hydrothermal environments dominated by island volcanism. Moreover, the contemporary microorganisms with the most ancient lineages based on molecular phylogenies are anaerobic, thermophilic, sulfur-metabolizing archaebacteria. These organisms were isolated from hot springs and hydrothermal vents where they thrive up to 105°C. Further inferences about the environments and environmental conditions that may have spawned Earth's earliest organisms must be gained by more micropaleontological and phylogenetic studies of past and present life, respectively (see Chapter 5).

Dry land probably existed on oceanic islands, island arcs, small continental masses, and the rims of impact basins. As noted below, in addition to the likely intense ultraviolet flux, rock vapor, ejecta, and tsunamis from large impacts would have made dry land an unfavorable place for the maintenance of life. Chemical weathering from dry land contributed chemical fluxes to the ocean as at present, but the size of these fluxes was relatively small. In contrast, hydrothermal vents in the ocean probably contributed

more of such fluxes than at present because plate tectonic rates were probably at least somewhat higher than now. The precise differences in ocean chemistry are not known, but they may not have been extreme because the ocean even at present is dominated or strongly influenced by hydrothermal vents for many elements. A reducing ocean depleted in sulfate and enriched in calcium, manganese, and iron seems likely.

The presence of ultramafic rock, either from ejecta or lava flows on land, also seems likely. At present, groundwater in such environments is basic and strongly enriched in calcium hydroxide. If calcium hydroxide is a necessary catalyst for organic synthesis (e.g., the formose synthesis of sugars from formaldehyde; see Chapter 4), it was probably more abundant in the Archean than now. Streams and freshwater springs draining ultramafic rock probably flowed both into the ocean and into more normal bodies of fresh water.

Impacts and Their Influence on Environmental Conditions for the Origin and Maintenance of Life

In theory, life could have arisen at any time after Earth was fully accreted and liquid water appeared on its surface (i.e., by about 4.5 billion years ago). At the same time, an early appearance of life would also have been subject to numerous environmental perturbations resulting from impacts, many of them potentially—if not outright—lethal.

Small bodies, up to tens of kilometers in radius, produced craters and may have perturbed the atmosphere in ways similar to those postulated for the impact at the end of the Cretaceous period. Among the global killing mechanisms for such impacts is believed to be the modification of the climate by the ejection of dust into the atmosphere, whereas direct impact, rock vapor, and ejecta would have resulted in only local effects. The tidal wave generated by an impact in the ocean was at least hemispheric. As proposed for the end of the Cretaceous period, small impacts may have killed many organisms but do not appear to have been a danger to the existence of life in general.

The case with larger bodies is less clear. Earth-like conditions would have returned after a brief interval after impact because the collisional energy was relatively small. For example, the energy of a collision with a 140-km-diameter object is equivalent to that of 100 years of sunlight on Earth. The conditions over the entire Earth's surface during the interval after such impacts may have been lethal because no place on Earth is far from the effects of a major impact.

The most lethal aspect of a large impact is the production of rock vapor. For modest impacts at asteroidal velocity, about 10 percent of the energy of

the impact is consumed in vaporizing a mass equivalent to that of the projectile. In a small impact, the vapor spreads out and cools by radiation. The rock vapor from a sufficiently large projectile overwhelms the Earth's atmosphere. Because the mass of the atmosphere is 5×10^{18} kg, the potentially lethal size of a projectile is somewhere between 30-km diameter, the rock vapor from which would heat the atmosphere 100 K, and 140-km diameter, the rock vapor from which would equal the mass of the atmosphere. The effect of rock vapor on life in the deep ocean is less clear because the mass (1.4×10^2 kg) and heat capacity of the present ocean are much larger than those of the atmosphere. For large impacts a transient water greenhouse traps much of the energy. A 400-km-diameter object would evaporate the ocean and evaporate life.

A second lethal aspect of large impacts is the generation of worldwide tsunami and the fouling of oceans with ejected material. These processes have not been modeled for large impacts, but it is clear that the tsunami heights are comparable to the ocean depth and that the ejecta mass is several times the mass of the projectile. The effects of rapid pressure change during the passage of tsunamis (many modern microorganisms can survive such pressure variations); chemical changes from catastrophic mixing of the ocean with condensed rock vapor, stirred up sediments, material eroded from the land, and ejecta; and longer-term heating of the ocean by hydrothermal circulation in the ejecta pile would almost certainly have been lethal even to some deep-sea life forms. Too little is known about the physics or the biology in such conditions to conclude whether all life was eliminated by large impacts early in the Earth's history. It is evident, however, that deep-sea organisms would have been much less vulnerable to the effects of such impacts than either life on land or life dependent on sunlight in shallow water.

The size and frequency of large impacts with the Earth can be constrained by studying the Moon because the record there has not been removed by later events. The youngest basin larger than 300 km in diameter, Orientale, is about 3.8 billion years old. There are 13 basins between it and Nectaris, which is between 3.9 and 4.1 billion years old. The surface is saturated with basins older than Nectaris, of which 30 have been identified. The largest confirmed (3.85 billion years) basin, Imbrium, is 1200 km in diameter. The largest postulated basins, South Pole (2500 km) and Procellarum (3200 km), formed very early and have been obscured by late events. Better dating of the lunar surface is needed to refine impact rates.

Obtaining an impact frequency for the Earth from the lunar cratering record requires adjustment for the different surface area and gravitational attraction of the planets. The lunar cratering rate at the time of Imbrium corresponds to about one large impact on the Earth every million years. (This corresponds to a rate of resurfacing less than that of present-day plate

tectonics.) It is much more difficult to compute the size of the projectiles that hit the Moon and, hence, the energy of similar objects hitting the Earth. Estimates of the energy involved in the formation of the larger lunar basins differ by two orders of magnitude, and no serious mathematical models have been made for large lunar impacts. Without such studies, one can only speculate whether large impacts precluded life or merely decimated it on Earth.

Prebiological chemical evolution and the origins of life could have occurred at any time after Earth accreted. If the gestation period for the planet to spawn life in near-surface environments was shorter than the interval between large-scale impacts, life may have arisen many times and been obliterated, or it may have arisen in surface environments and migrated to deep-sea niches following the development of a network of hydrothermal environments that bridged shallow and deep marine locations. Once protected in deep ocean niches, it might have survived numerous impacts and possibly served as dispersal centers to repopulate shallow marine environments.

These speculations on chemical evolution, multiple origins of life, and models of early environmental conditions in the atmosphere and oceans can only be substantiated by the geological record. Ancient rocks of all types—especially samples of sedimentary environments—are critical, and efforts to find them are of high priority. The very processes of impacts and tectonism appear to have obliterated all but traces of the early record of Earth, however. For this reason it is essential to extend the search to Mars, where an early planetary history parallel to but less violent than Earth's may have prevailed and where the record must be better preserved.

Mars

Mars continues to be the extraterrestrial body that holds greatest promise of scientific return on fundamental questions about the origin of life. Although the results from the Viking Biology and Molecular Analysis experiments were not necessarily representative of the planet as a whole, the likelihood of extant life on Mars appears low. On the other hand, there are reasonable prospects that evidence of chemical evolution and fossil life might be found. As is true for Earth, the key to understanding the occurrence or absence of chemical evolution, the origin of life, and extant life on Mars lies in deciphering the planet's history of water, its geochemical cycles, and its atmosphere.

OBJECTIVE 3: *To assess the isotopic, molecular, morphological, and environmental evidence for chemical evolution and the origin of life on Mars.*

Aqueous Environments

The conditions over most of the surface of Mars today are extremely hostile to life. Of particular importance are the low temperatures and the apparent lack of liquid water. Several lines suggest, however, that local and seasonal aqueous environments may be possible at the present time.

The partial pressure of CO_2 (and, therefore, the total atmospheric pressure) is probably dynamically maintained near the triple point of water by the weathering of silicates and the release of CO_2 from the interior by volcanism and metamorphism. At equilibrium, weathering reactions, such as

$$CaMgSi_2O_6 + CO_2 = CaCO_3 + MgSiO_3 + SiO_2,$$

would reduce the partial pressure of CO_2 by orders of magnitude. These reactions, however, proceed very slowly in the absence of liquid brine (or water). An increase in atmospheric pressure leads to greater stability of brines, more weathering, and then a decrease in atmospheric pressure. Conversely, a decrease in atmospheric pressure retards weathering and allows metamorphism and volcanism to recharge the atmosphere.

A similar situation exists on the Earth. The bulk of the CO_2 is in sedimentary rocks. A decrease, for example, in metamorphism would lead to less gas in the atmosphere. The lack of a greenhouse would then cause lower temperatures. This would retard the loss from weathering and stabilize the cycle.

The channel systems on Mars strongly suggest that an aqueous surface environment existed in the past in many areas. The poorly developed nature of the drainage networks indicates that springs, rather than rain, fed these channels. These fluvial features appear to have formed early on, probably in the first billion years of Martian history during the period when life arose on Earth, and may represent sites occupied by the first organisms to have arisen on Mars. In addition, photogeologic evidence suggests the presence of stratified sedimentary deposits on the floors of canyons in the Valles Marinaris system. These deposits imply sedimentation in standing bodies of water, in which case lake environments may also have served as habitats for Martian life.

The low rate of crustal recycling on Mars might have affected the maintenance of life. Surface layers might have become leached of nutrients. However, if life exists only in limited areas, wind-blown dust might represent a reservoir for nutrients, provided that the trace amounts of oxidants found in the soil by the Viking experiments did not exert a sterilizing effect at the surface.

The rugged topography, numerous faults, and frequent sedimentary or volcanic stratification imply that aquifers may channel brines into springs

on Mars. Warm (~273 K) springs are possible where high topographic relief causes deep circulation of the brines. Wet muds can exist seasonally in such environments, but more rapid recharge is needed to maintain pools.

Radar reflectivity appears to be the best method of searching for the distribution of brines. Seasonal reflectivity anomalies have been interpreted to indicate widespread brines at shallow depths. Very high resolution methods may be needed to find springs and brine pools.

Differences Between Mars and Earth

The Earth has large oceans, whereas no large bodies of surface water exist on Mars. A drastic differencê in the amount of degassing is not required to explain the lack of water on Mars because of the different style of tectonics on the two planets. Consider the difference between the rock cycles on the Earth and on Mars. To start with mass balances, the oceans on Earth are equivalent to a uniform layer 2500 m thick and the water in sediments is equivalent to an additional 200 m. The total water on Mars at the time the channels formed has been estimated to be approximately 500 m or one-third of the Earth's per mass. On the Earth, sediments are deposited preferentially along continental margins. The pore space in these sediments is destroyed by low-grade metamorphism, and the water in hydrated minerals is released by higher-grade metamorphism. Metamorphism is particularly frequent for sedimentary rocks near continental margins. The sediments themselves are uplifted and eroded so often that most sediments are recycled sedimentary rocks. There are no deep depressions in which sediments can accumulate and remain undisturbed. The ocean basins are continually swept clean and renewed by plate movements. Old unmetamorphosed sediments are thus rare on Earth. Dry sediments are similarly rare.

In contrast, there are no plate tectonics on Mars. Other tectonic and igneous processes are also much less active on Mars than on Earth. Thus, sediment can accumulate in depressions and not get metamorphosed. In addition, much of the planet is covered with basaltic lavas and some areas with old impact ejecta. Such rocks are likely to be porous. Liquid water reacts readily with basalt (or basaltic sediments). The water of hydration in fully hydrated marine basalts is around 3 percent by mass or 10 percent by volume. The amount of hydration is even higher if there are extensive ultramafic volcanics, as indicated by the analysis of meteorites attributed to Mars. Similar amounts of hydration might be expected on Mars. The heat flow and, hence, the geothermal gradient on Mars are likely to be less than those of inactive areas on the Earth. Metamorphism sufficient to release water of hydration on Mars is likely to be very local. The lower geothermal gradient, the lower gravity, and the likely presence of ice at shallow depths all aid the preservation of pore space on Mars. A few hundred meters of

water could easily be locked up in ice and groundwater if the layer of porous rocks is a few kilometers thick. A similar amount could be present in clays. The formation of channels probably ended when the bulk of the water became locked up and tectonic and metamorphic processes became too sluggish to recycle the water.

The behavior of ice is also considerably different on the two planets. On Earth, large glaciers can exist only on land and usually at high latitudes. The thickness of ice is limited by its flow. In particular, ice flows more easily near the base of a glacier because the geothermal gradient means it is hotter there and because ice melts at lower temperatures under higher pressures. The lower gravity and geothermal gradient on Mars, combined with a much larger area of the planet on which ice can accumulate and a lower inventory of water, tend to preclude rapidly flowing continental glaciers on Mars. This allows water to be locked up as ice for considerable periods of time.

Much can still be learned from theoretical models of Mars that include the physics and chemistry of the atmosphere, the groundwater, and ground ice, as well as metamorphic processes and weathering reactions. As noted above, brines may be detected by radar. Nearer-surface geophysical methods are probably necessary to study the thickness of ice and the extent of porosity in sediments. Returning samples of Mars to Earth may be necessary to examine weathering in detail.

Large Impacts on Mars

Large impact basins are observed on Mars even though much of the surface is younger than these events. The hazard to life by the impacts would have been much less than the hazard on the Earth because the gravitational potential of Mars is much smaller. A low-velocity impact of an object with a similar orbit generates little rock vapor. A high-velocity impact generates rock vapor, but the vapor escapes into space rather than surrounding the planet. The effects of ejecta and tidal waves on the ocean on Earth are also not likely to be applicable to Mars. Thus, large impacts were probably lethal only to those Martian organisms (if any) that were obliterated in the impact crater or buried by thick ejecta.

Prospects for Chemical Evolution and the Origin of Life on Mars

Among all the scientific opportunities provided by NASA's space missions, the return of samples from Mars for study in Earth laboratories (e.g., by the Mars Rover/Sample Return Mission) holds highest priority. It provides a unique opportunity to address within the solar system the fundamental issues of chemical evolution and the existence of life on another Earth-

like planet, on the one hand, and the possible uniqueness of life on Earth on the other (cf. SSB, 1977, 1981).

Not only does present knowledge of the ancient Martian surface indicate that early environments on Mars were similar to those at the same time on Earth, the environmental record of Mars' first billion years is potentially far better preserved than that on Earth, where continuing tectonic activity has destroyed almost all evidence. Samples of Mars can fill the gap in the Earth's geological record. In addition, the prospect of finding evidence of chemical evolution on Mars is as important as evidence of fossil life. Primordial organic matter on Mars may be preserved at depth in the regolith or in ancient sedimentary deposits protected against destruction by oxygen, ozone, and other oxidants in the atmosphere and surface dust.

Mounting evidence, some alluded to in the preceding section, indicates that Mars' surface environment 4.5 to 3.5 billion years ago was quite different from the Mars of today. Early Mars and the early Earth are compared in Table 3.2. The primary evidence suggesting that Mars' early history may have been conducive to chemical evolution and the origin of life is the presence of many geological features that can only be attributed to liquid water. Most persuasive of these is the evidence for extensive valley net-

TABLE 3.2 Comparison of Early Earth and Early Mars

Property	Early Earth	Early Mars
Water	Oceans	Evidence for surface liquid water hydrological cycle (?)
Temperature	>273 K	≅273 K
Atmosphere	CO_2, N_2, H_2O: >1 atm	CO_2, N_2 (?), H_2O: ≅1 atm
Geochemical carbon cycle		
$CO_2 \rightarrow$ carbonate rocks	Reactions in water	Reactions in water
Carbonate rocks $\rightarrow$ CO_2	Continued subduction, metamorphism, and volcanism	Early volcanism and metamorphism only
Duration of thick atmosphere	4.4 billion years (?) $\rightarrow$ present	4.4 billion years–3.5 billion years (?)
Preservation of rock record	Highly altered and reworked	Ca. two-thirds surface is >3.8 billion years old
Biology	Diverse life at 3.5 billion years	

works believed to have been caused through erosion by running water. The valley networks are present over most of the ancient cratered terrain on Mars, implying that the period of water activity extended from before to somewhat after the decline in impact rates some 3.8 billion years ago. It is clear from the length and size of the valley networks that liquid water was stable at the surface This in turn implies that early Mars must have had a substantial atmosphere with correspondingly higher temperatures and pressures than at present.

Current models of planetary accretion and atmospheric evolution suggest that this atmosphere was primarily composed of CO_2 at a pressure of one to several atmospheres, with some N_2 present. The amount of nitrogen in the atmosphere of early Mars may have been as small as it is today; if so, this may have had important implications for chemical evolution and the origin of life. Despite its present appearance of tectonic quiescence, the huge shield volcanoes and rift valleys attest to considerably more volcanism and outgassing, as well as higher heat flows, much earlier in the planet's history. The duration and fate of Mars' early atmosphere are uncertain, but it is probable that the CO_2, like water, was trapped chemically (as carbonate) and physically within the regolith over time. Possibly a thick CO_2 atmosphere could have been maintained by volcanism for as long as a billion years. Without tectonic activity, which recycles Earth's sediments, it was almost inevitable that Mars would lose its atmosphere.

Despite their differences today, the young Mars may have been similar to the young Earth in terms of several environmental features critical to chemical evolution: moderate temperature active tectonism, the presence of liquid water, and the occurrence of biogenic elements in the atmosphere and surface rocks. It would have been within this environmental context that the process of chemical evolution might have occurred and left some relict evidence (see Chapters 4 and 5) in the geological record. Because well-developed microbial ecosystems evolved on Earth well within its first billion years, the exciting possibility that life also arose on Mars provides a compelling reason for pursuing the active exobiological study of this planet.

Because water plays such a critical role in biological and other surface processes on Earth, there is every expectation that Mars sites associated with water activity are the best places to look for evidence of chemical evolution and fossil life. These same sites are also the most suitable for studying the geochemical cycles and paleoclimates of the planet. Thus, there are compelling reasons for assigning high priority to the return of Martian samples that retain a record of liquid water activity, particularly from ancient water-laid sedimentary environments.

To provide the scientific basis for the search for ancient life on Mars, the similarities and differences between the early surface environments of Earth and Mars must be considered in detail. (An example of key differences

may be the atmospheric pressure of N_2.) A comparative understanding of the planetary environments, coupled with a knowledge of the physiological and ecological requirements of putatively analogous ecosystems such as Antarctic microbial mat systems, would prove valuable in this effort. The model scenarios coupled with field techniques of micropaleontology will be essential for the development of experimental protocols for in situ investigations of Martian sediments. These issues are addressed in detail in Chapter 5.

The committee wishes to emphasize that exobiological interest in Mars is not limited to a simple search for microfossils—although such an investigation would certainly be part of any sample analysis strategy. Exobiologists are interested in a comprehensive examination of Martian sediments and other samples, including isotopic geochemical analysis of hydrogen-, carbon-, nitrogen-, oxygen-, sulfur-, and phosphorous-bearing materials in igneous rocks and the atmosphere; organic geochemical studies of any preserved organic materials; and inorganic geochemical and mineralogical studies of clays, carbonates, sulfates, phosphates, and other phases that are composed of the biogenic elements and are associated, at least on Earth, with water or biological activity. Data from such studies will reveal the history of the biogenic elements and water on Mars and factors in the development of the planet that may have influenced the progress of chemical evolution toward living systems. Clearly, the suite of data germane to exobiology overlaps that sought by a broad range of other disciplines interested in Mars. The committee notes that such an investigation will be scientifically meaningful whether or not evidence for extant or extinct life is found. Either result is important for understanding the origin and evolution of life on Earth and other planets throughout the cosmos.

4

The Origin of Life

What sparked the origin of life on the early Earth? As historians, we must gather our records and try to make sense of them. There are, at present, four primary sources of information: (1) the record of the early solar system, as preserved in comets or carbonaceous chondrites and on the surfaces of Mars or the Moon; (2) the record of terrestrial rocks—geology; (3) the record of ancient microorganisms and their physiological activities—paleobiology; and (4) the phylogenetic history recorded in the nucleotide and amino acid sequences found in living cells—molecular phylogeny. According to the geological record, the Earth appears to be 4.5 billion years old. The oldest extant supracrustal rocks, the Isua formation in Greenland, are 3.8 billion years old, but they are rather strongly metamorphosed. The earliest solid evidence for life is found in stromatolitic formations in Western Australia and South Africa, dated as 3.5 billion years old. However, evidence may yet be found that life was present on Earth more than 3.5 billion years ago.

Unlike historians, however, in addition to the record, scientists can also take a constructionist approach: they can simulate in the laboratory conditions that may have existed on the prebiotic Earth and see what their consequences are. Both approaches have been productive, and together they may eventually solve the problem of how life arose on this planet. Following are examples of these two approaches:

- Model systems for synthesizing fundamental biochemical monomers: Here, theory is employed—for example, models of the solar nebula and planetary accretion—to deduce the likely composition of the early atmosphere and then to observe what compounds are produced when this type of mixture is subjected to various forms of energy such as ultraviolet light, shock waves, or coronal discharge. An early example of this approach was

the well-known Miller-Urey experiment, in which amino acids were produced when an electric spark was passed through a mixture of methane, ammonia, hydrogen, and water. More recent models of the early Earth suggest a less reducing atmosphere. Evaluation of these alternative models necessitates new conjectures and experiments as to how the biologically important monomers were formed and what substituted for hydrogen as a reductant.

- Comparative molecular biology: Here, an attempt is made to deduce the characteristics of the earliest cells and cellular mechanisms by inspecting contemporary organisms for features that are common to the three primary lines of descent: eubacteria, archaebacteria, and eukaryotes. The assumption is made that any feature found in all three lines was probably present in the ancestral organisms from which the lines derived.
- Models for replication: Replication is essential for life. The nature of DNA (deoxyribonucleic acid), a complementary double helix, has inspired a number of experimental models for primitive replication. The most extensively studied of these is Orgel's system for template-catalyzed polymerization of activated nucleotides. However, the discovery of catalytic RNA (ribonucleic acid) has led to several intriguing suggestions as to how RNA could have catalyzed its own replication. A proposal for the templated replication of clays, made by A. G. Cairns-Smith, has inspired some experimental model systems that are now being examined.
- Models for the origin of gene expression: Since 1963 it has been recognized that one of the most difficult problems in studying the origin of life has been the origin of translation, the process whereby the sequence of nucleotides in a nucleic acid specifies a sequence of amino acids in a polypeptide. Several suggestions have been made for the origin of this complex coupling mechanism, but these have not been evaluated experimentally.
- Comparative planetology: The study of Mars, Venus, and the Moon should help to reconstruct the early history of the Earth. The early history of this solar system often can be read more easily elsewhere than on Earth. The origin and evolution of the solar system must be understood. As discussed in Chapter 3, the exploration of Mars will bear importantly on a perspective of the origins of life on Earth.

It must be emphasized that the study of the origin of life is a highly interdisciplinary endeavor, and the most productive work in this field increasingly will be done in that context. The recent discovery of catalytic RNA is a case in point. This finding brought new ideas (and practitioners) into the study of origins, but some of the new theories seem inconsistent with the environmental conditions in which the reactions are imagined to have taken place.

In this chapter, four major goals are discussed, together with objectives pertaining to these goals. These objectives, as a whole, address models and

experimental approaches to the study of the origin and evolution of metabolism, replication, and translation.

GOAL 1: *To understand the origin and evolution of metabolism in primitive life forms.*

The 1981 report of this committee (SSB, 1981) gave an overview of the nonenzymatic synthesis of biological monomers in an atmosphere of methane, nitrogen, ammonia, and water. A portion of that report follows:

> Many of the monomers synthesized enzymatically by cells are thought to have originally accumulated spontaneously on Earth as a result of nonenzymatic reactions. These include amino acids, components of proteins and nucleotides, components of nucleic acids (DNA, RNA). This concept derives from many observations that gaseous mixtures, for example, methane, nitrogen, ammonia, and water, if supplied with energy such as spark discharges, produce the amino acids including those found regularly in proteins. The distribution of monomers so produced is qualitatively and quantitatively similar to that found in carbonaceous meteorites. In addition, most protein amino acids may be produced nonenzymatically starting with simple organic compounds such as formaldehyde and hydroxylamine.
>
> Furthermore, the abiotic routes of formation of all the components of DNA and RNA are known. Sugars easily form spontaneously from formaldehyde; polymerization occurs under alkaline conditions. The condensation of hydrogen cyanide in the presence of ammonia produces amino acids as well as the purine nucleotide bases, adenine and guanine, components of all nucleic acids. Cytosine, a base found in nucleic acids, can be readily synthesized from cyanoacetylene. By deamination, cytosine yields another major base of RNA, uracil. Thymine, a major base of DNA, which, in today's genetic code is informationally equivalent to uracil, can be formed from the condensation of uracil with formaldehyde. In the presence of phosphate the phosphorylated forms of the nucleotides of these bases can be produced nonenzymatically. Fatty acids may be formed from carbon monoxide and hydrogen in the presence of nickel-iron catalysts, catalysts that might have been brought in by meteorites. Glycerol is a component of fats that has also been obtained nonenzymatically in the laboratory by reduction of glyceraldehyde. Glyceraldehyde itself, a common intermediate in cell energy-yielding reactions, may be formed by condensation of formaldehyde under alkaline conditions.

Thus, in the 1981 report, the problem of monomer synthesis was considered solved. However, in recent years, reasonable models suggest that the primitive atmosphere of the Earth consisted largely of CO_2, N_2, and water vapor. At the same time, preliminary studies have indicated that spark discharge in such an atmosphere results in the formation of nitric acid. Hence, the question of the synthesis of organic compounds on the prebiotic Earth is far from settled and must be reexamined.

Achieving an adequate level of understanding of these issues entails the

attainment of many objectives, the most important of which are described below.

OBJECTIVE 1: *To reexamine the prebiotic origin of biomolecules in environments suggested as probable on the primitive earth.*

One proposal (discussed in Chapter 3) is that reduced organic compounds were brought to the Earth in comets and meteorites. Another suggestion is that CO_2 was photoreduced by ferrous ion (Fe^{2+}) in water. The banded iron formations that are found in the oldest terrestrial rocks (3.8 billion years old) suggest that the photochemistry of Fe^{2+} in water played a significant role on the early Earth. Sulfides in hot springs and ocean vents also have been suggested as possible reductants of CO_2. These new possibilities have raised the question of the nature of the earliest metabolism. Did cells first form in an environment where monomers were abundant and then gradually evolve a photosynthetic capacity, or was photoreduction of CO_2 and N_2 a prerequisite for the first self-replicating entity? It seems likely that the Western Australian stromatolites were formed by photosynthetic organisms, but to what use was the light energy put? These questions require careful study, including detailed comparative analysis of contemporary metabolic pathways.

Sulfide may have been abundant on the early Earth, yet it has received little experimental attention with regard to its possible involvement in prebiotic syntheses. Hydrothermal vents and hot springs are rich in sulfide and have been suggested as sites of prebiotic synthesis. Thiol esters are more reactive than oxygen esters in many reactions and are important in contemporary biochemistry.

OBJECTIVE 2: *To explore mechanisms for sequestering biomolecules on a surface or within vesicles (compartmentation).*

The evolution of biological mechanisms makes sense only if they are sequestered from the environment and protected from dilution. This implies the adoption of some form of compartment. The membranes surrounding contemporary cells are usually based on some form of phospholipid. These commonly contain glycerol, fatty acids or alcohols, phosphate, and one of several other possible molecules. However, the prebiotic syntheses of long-chain fatty acids and alcohols have presented some difficulties.

This area of study, leading to plausible prebiotic mechanisms for the synthesis of molecules that could have formed vesicles, consistent with present knowledge of the composition of the early atmosphere, is important to understanding the origin of cellular metabolism. Also necessary is the study of reactions of energy-harvesting molecules that could have been encapsulated inside lipid vesicles.

OBJECTIVE 3: *To identify and characterize chemical systems capable of coenzyme functions in a prebiotic context.*

The role of coenzymes in the evolution of metabolism is important but understudied. Some workers have pointed out that the nucleotidelike structure of many coenzymes suggests that RNA may once have carried a greater variety of functional groups than it does today and may therefore have been a more versatile catalyst: for example, NAD-RNA (nicotinamide adenine dinucleotide and ribonucleic acid) as a potential redox catalyst. These ideas are testable experimentally, because the required molecules can be made with the aid of the enzyme T4 RNA ligase. Other rudimentary coenzyme mechanisms should be sought: for instance, some coenzymes have been activated by Al^{3+} or by absorption on clays.

OBJECTIVE 4: *To investigate the nature of the earliest type of cellular metabolism.*

If two disparate groups of organisms evolved from a common ancestor, then characteristics that are common to the two groups probably were present in the ancestor. For example, the ability to obtain energy from sulfide oxidation is distributed throughout the prokaryotic lines of descent: the archaebacteria and the eubacteria. If the mechanisms of sulfur oxidation in these two groups of bacteria are similar, then—barring lateral transfer—it is probable that their common ancestor oxidized sulfur in the same way. Focusing on sulfide oxidation is particularly interesting because it likely was abundant on the early Earth, and there is evidence that the earliest known stromatolitic communities were affiliated with hydrothermally active (hence sulfide-rich) environments.

GOAL 2: *To understand the origin and evolution of replication.*

Replication is the process whereby a copy is made of a genetic molecule. This must be done in such a way that the information content of the molecule is preserved; the parent molecule must somehow serve as a template for its progeny. The replication process is the essence of life.

It is widely believed that reactions simpler than, but similar to, nucleic acid replication and protein synthesis appeared very early in the history of life on Earth. Any attempt to provide a chemical model of the evolution of these coupled processes must grapple with a fundamental problem: nucleic acids are molecules that seem ideally suited for replication, whereas polypeptides seem similarly suited for function. However, at least in contemporary systems, nucleic acids cannot replicate without the help of well-defined protein catalysts, and the synthesis of well-defined protein catalysts is impossible without the direction of nucleic acids. How might a coupled system of proteins and nucleic acids have started? Various suggestions for the solution of this "chicken and egg" problem have been discussed:

- Early functional proteins replicated directly. They "invented" nucleic acids and were ultimately enslaved by them.
- Early nucleic acids or related molecules replicated independently of proteins. They "invented" protein synthesis. Uncoded polypeptides may or may not have been involved in the earliest precoding replication mechanisms.
- Nucleic acid replication and genetic coding of proteins coevolved.
- The first form of life on Earth was based on a self-replicating system that contained neither nucleic acids nor proteins. The suggestion has been made, for example, that it consisted of a family of self-replicating clay particles. The early system gave rise to the nucleic acid/protein system or a precursor of it.

Claims that the spontaneous polymerization of amino acids leads to the formation of long, highly ordered oligomers are implausible. No detailed mechanisms for the residue-by-residue replication of proteins have been suggested, and the possibility that a protein-copying enzyme could evolve spontaneously is unlikely. Thus, the first suggestion above seems untenable.

The "nucleic-acid first" theory has generated a good deal of experimental effort. Nonenzymatic template-directed synthesis has been studied extensively, particularly by L. Orgel and his co-workers. It has been established that a preformed template does indeed facilitate the synthesis of its complement, according to the Watson-Crick pairing rules. The template CCCGCCCGCCCGCC facilitates the synthesis of all of the oligomers up to GGGCGGGCGGGCGGG, with exclusively 3′–5′ linkages under appropriate conditions.

The discovery of RNA molecules that catalyze the cleavage and joining of oligonucleotides was revolutionary. Thus, an RNA molecule might be able to function as an RNA polymerase by catalyzing the nonenzymatic template-directed reactions discussed above. If so, a replicating system based on RNA without proteins certainly seems possible. On the primitive Earth, "RNA life," in which RNA molecules catalyzed a limited set of metabolic reactions in addition to RNA replication, may have preceded life as we know it. However, it remains problematic because

- as yet there is no known route from a simple prebiotic environment to a self-replicating RNA;
- no prebiotic synthesis of ribose has yet been found that does not also produce a wide range of other sugars;
- the condensation of ribose with bases would give complex mixtures of products, including L- as well as D-nucleosides, and nucleosides with α- as well as those with β-glycosidic linkages; and
- presently known region-specific and efficient syntheses of internucleotide bonds require special conditions.

OBJECTIVE 1: *To search for simple organic replicating systems.*

Template-directed replication with ribonucleotides is the most straightforward, experimentally accessible, general model of replication. However, even simpler systems warrant experimental study. It would be important to search for simple nucleotidelike monomers—and for even simpler "protonucleic acid" models—that use inorganic backbones in place of covalently linked organic backbones. For example, simpler structures such as glycerol phosphates that carry a heterocyclic base can participate in template reactions and form a glycerol pyrophosphate backbone capable of replacing the standard nucleotide backbone.

OBJECTIVE 2: *To investigate the possible role of RNA catalysis in replication.*

It is clear that RNA can exhibit catalytic activity, as well as serve as a template in replication. Thus, it seems more likely than ever before that RNA was an important primordial molecule. RNA molecules have been demonstrated to have specific hydrolytic and ligating activities, and they can act as simple polymerases by extending preexisting RNA chains at the expense of other preexisting ribooligonucleotides. RNA can also act as a phosphate monoester transfer catalyst and phosphomonoesterase. Perhaps the earliest form of life capable of evolution was an RNA molecule or had an RNA genome.

The enzyme RNase P (ribonuclease P) and the self-splicing RNAs, both involved in posttranscriptional RNA processing, will prove to be the first known members of a longer list of RNAs that carry out, or are associated with, catalysis. Extension of this list is desirable. Experimental surveys of enzymatic activities that have RNA components, or are sensitive to ribonucleases, constitute one way to generate a list of activities for investigation. Such surveys should have the widest possible phylogenetic basis.

Current methods for the characterization of RNA structures of any complexity present a serious limitation in the study of RNA. Development of this area would be facilitated by the dissemination of methods for the synthesis of RNAs of known primary structure and by support for single-crystal x-ray studies on suitable synthetic models. A systematic set of high-resolution RNA helices, "loops," and "hairpins" would provide a grammar for expressing the structure of more complex RNAs than is now available. Such information has greatly stimulated study of the activities of DNA, and the lack of similar grammar limits the syntax of hypotheses about RNA function. Complementary to this work are methods for predicting and confirming the solution structures of complex RNA molecules, for example, by two-dimensional nuclear magnetic resonance (NMR).

Modern RNA-based organisms, such as viroids and virusoids, have a

style of life and simple molecular structure that seem likely to pose novel and soluble questions about RNA propagation and activity. The positive-strand RNA viruses (in either prokaryotic or eukaryotic hosts) and other freely replicating RNAs are particularly interesting. It is in these molecules that ancient connections between genotype and phenotype may still exist or have been reestablished. That is, these are modern molecules that must replicate, that often participate directly in translation (as messages), and that may also have the potential to carry out catalysis. Where modern cells have preserved ancient biochemical capabilities, it is possible that these processes can be isolated for examination in a virus or small RNA.

The isolation, sequencing, and study of small RNAs from the widest possible diversity of cells may well provide new insights into the fundamental role of RNA in replication.

OBJECTIVE 3: *To determine the mechanism of clay formation in nature and in the laboratory and the possible relevance of clay to replication.*

Clays were first implicated in the origin of life by the British crystallographer J. D. Bernal in 1951. He considered that monomers such as nucleotides and amino acids could be adsorbed from dilute solution onto a clay surface and there polymerized to give proteins and nucleic acids.

Clays are made up of various ions embedded in a two-dimensional silicate lattice. The elements involved are mainly silicon, oxygen, aluminum, iron, and magnesium. Clays are formed when water causes the chemical weathering of rocks. The concentration of ions in clays is extremely variable; the surfaces of clays usually have a net negative charge that is neutralized by a positive counter-ion (e.g., Na^+, K^+, Mg^{2+}, Ca^{2+}, Zn^{2+}, Fe^{2+}). The mineral theory of the origins of life postulates the existence of a family of clay particles having two remarkable properties. First, they must have surface structures so specific and detailed that they can catalyze the organic reactions necessary to initiate "organic life" (and different clones of clays may differ markedly in their ability to catalyze specific organic reactions). Second, they must be able to replicate to produce "daughters" having the same remarkable catalytic activity.

In 1965, Cairns-Smith proposed that the original genes may have been clays. He suggested that the distribution of ions such as magnesium and iron could play the role of the bases of DNA. The "genetic" information would be stored as the distribution of ions in the different layers. The idea was that clays not only could adsorb and catalyze reactions between organic molecules but could, like DNA, replicate. Thus, two sheets of clay would be like the two complementary strands of a DNA molecule. Ion substitutions in one clay sheet would give rise to a complementary pattern on the clay synthesized on its surface. If, as with DNA, an error of replication or mutation is possible, then replicating clays could evolve.

Although experimental evidence in support of these ideas is meager, the committee feels that they merit further study, particularly with regard to template and catalytic aspects of clay lattices.

GOAL 3: *To understand the origin and evolution of gene expression.*

The origin of translation—protein synthesis—is one of the most difficult problems in studying the origin of life. In this process a sequence of nucleotides in an RNA message codes for a sequence of amino acids in a protein. The complex system of ribosomes, transfer RNAs (tRNAs), and aminoacyl-tRNA syntheses has proven difficult to model. All three primary lines of descent—eubacteria, archaebacteria, and eukaryotes—contain the recognizable elements of a single type of ancestral ribosome. Thus the replication/translation apparatus appears to predate the divergence of these three lines and presumably was present in the "progenote," the earliest cell.

The function of the contemporary ribosome is far from understood. One early suggestion, still tenable, was that the ribosome acts to isolate the codon-anticodon interaction from the solvent. The ribosomal proteins differ widely among different organisms, whereas the ribosomal RNA (rRNA) is much more conservative in its sequence and higher-order structure. This suggests that the essence of the translation process lies in rRNA.

The process of translation is fundamentally coupled to the genome through the genetic code in all extant organisms. Establishment of this couple must be regarded as an essential event in the emergence of the first true organisms from a population of progenitors that lacked it. This development allowed the earliest organisms to express individual identity.

To understand the origin of the translation apparatus and the genetic code, comparative molecular studies of extant systems are necessary to gain detailed insight into the essential workings of these processes in modern organisms. This information should allow the construction of meaningful models for primitive versions of the processes that are best tested by a direct study with synthetic polymers, in the tradition of prebiotic chemical studies.

OBJECTIVE 1: *To determine the origin of codon assignments.*

There are two classes of theories relating to the origin of the genetic code. Models of the "frozen accident" type suppose that the codon assignments arose randomly. Other models hypothesize that particular codon assignments reflect affinities between amino acids and nucleotides.

Frozen accident models, by their nature, are not readily testable. However, the notion of a specific relationship between codons and amino acids is. The interaction between amino acids and nucleotides has been under study for some years. These interactions are weak in water, and ways to amplify them, and increase their specificity, are being sought. The necessity

for further activation of the amino acids and proper alignment for polymerization into peptides also constrains experimental models. Proponents of specific association models have argued that studies of the interaction of the aminoacyl-tRNA synthetases with their cognate tRNAs could provide important insights. Numerous biochemical studies of this interaction have been made, but the system is complex and fundamental principles have not emerged. Nonetheless, recent advances in recombinant DNA technology and the synthesis of oligonucleotides, coupled with advanced physical techniques, encourage the study of model interactions between polynucleotides and amino acids and peptides.

Although it has not been widely appreciated, any stereochemical explanation for the codon assignments must be coupled to the molecular mechanics of translation. Thus, it has been suggested that early forms of tRNAs may have been able to fold up in such a way that the nucleotides of the anticodon would sit close to the amino acid that is esterified at the 3′-terminus. Because a hydrophobic amino acid tends to have a hydrophobic anticodon, a mutual interaction of the esterified amino acid with its anticodon might stabilize the amino acid ester bond against hydrolysis. The result would be a preference for a hydrophobic amino acid to remain in the site adjacent to a hydrophobic anticodon. Additional specificity could come from steric or polar interactions between the amino acid side chain and the anticodon nucleotides.

Further evidence should be sought for specific interactions of amino acids and amino acid derivatives with their codonic and anticodonic nucleotides. Possible amplification of these interactions by the addition, for example, of micelles, lipid vesicles, or simple oligopeptides should be investigated.

Following the establishment of the genetic code in the early 1960s, many studies were conducted to determine the universality of the codon assignments; however, because of the limited sampling of phylogenetic diversity, these studies revealed no variation among species. Not until the 1980s did sequence studies uncover several variant codon assignments in mitochondria. At first, these could be attributed to degeneration of the organelle translation machinery. Subsequently, additional coding variations were found in both prokaryotic and eukaryotic organisms. The extent of variation is still unclear. The existence of deviations from code universality must be reconciled with both the origin of the code and the molecular mechanics of translation.

OBJECTIVE 2: *To understand the molecular mechanics of translation.*

The translation apparatus is a complex machine with many component parts, reflecting eons of evolution that have embellished the essential apparatus in order to fine-tune the process. The mechanism of translation is of

central interest to exobiology because it is quite reasonable to assume that, once established, the actual mechanics of translation remained largely unaltered. This view is supported by comparative studies of ribosomes from all known organisms. However, it also is expected because the nature of evolutionary processes is to prefer fine-tuning to drastic revision.

The interaction of tRNAs with messenger RNA (mRNA) is clearly a dynamic process. The binding of the aminoacylated tRNA to the mRNA triggers the synthesis of a peptide bond and the subsequent repositioning of mRNA, relative to tRNA, by three nucleotides. Two types of models have been proposed for this process. In the conventional "A site/P site" models, tRNAs are imagined to be relatively static structures that are transferred physically from one location to another, carrying mRNA along with them. "Ratchet" models propose that tRNA enters the ribosome and remains at one location but subsequently undergoes conformational changes that result in the movement of mRNA relative to tRNA. In both models, the actual synthetic step occurs at the 3′-end of the tRNA, which is a considerable distance from the site of the codon-anticodon interaction. In either case, coordination must occur between the synthesis and the "translocation" event. This might be accomplished by kinetic means or, conceivably, by the transmission of a signal through conformational changes.

Recent results suggest that significant progress in understanding the translation apparatus may be made by studying model systems. It is known, for example, that the anticodon helix and loop alone will bind to 30S and 70S ribosomes in a codon-specific manner but that RNAs smaller than the helix and loop are impaired in ribosomal binding. Likewise, the translational process is known to continue at a low rate without the ancillary factors associated with cellular protein-synthesizing systems. Finally, recent molecular dynamics calculations suggest that the CCA terminus of tRNA may be capable of significant motion.

Because recent advances in RNA technology make possible the synthesis of RNAs having a defined sequence, this capability should be used to explore possible models for the primitive translation machinery.

The committee believes that knowledge of the molecular mechanics of translation in modern organisms will provide insight into the origin of translation. This belief reflects the evolutionary principle that a fundamental process such as translation is likely to be highly resistant to change in its essential character once it is established. At the least, knowledge of the modern mechanism is basic to understanding the origin of the process.

OBJECTIVE 3: *To conduct a phylogenetic-comparative dissection of the translation apparatus.*

The extraordinary conservation of the rRNAs in sequence and higher-order structure, coupled with the discovery of RNA catalysis, makes it a

reasonable speculation that the activities of the ribosome may reside in the rRNAs. Beyond this, the processes of codon-anticodon interaction and movement of the mRNA relative to the ribosome may also require the involvement of parts of the rRNAs. It may be possible to identify which elements of the rRNAs are likely candidates in these processes. For example, extensive portions of the RNAs are clearly dispensable, as is seen by their absence in mitochondrial rRNAs. In this regard, efforts should continue to elucidate the three-dimensional arrangement of the evolutionarily conserved segments of the rRNAs within the ribosome in order to identify regions that perform an active role in translation. This will require a combination of approaches using theoretical and experimental methods.

GOAL 4: *To determine the evolutionary events leading to the accretion of complex genomes.*

Current theory argues that early RNA genomes gave rise to DNA genomes, partly because DNA is chemically more stable and, hence, more amenable to storing large numbers of genes. We do not know at what stage in the evolution of cellular replication this might have occurred. Presumably the change from an RNA-based genome to a DNA genome occurred prior to the divergence of the primary lines of evolutionary descent. The earliest cellular unit must already have acquired many genes, as required for replication, energy transduction, and at least a rudimentary translation apparatus. Such complexity may have arisen from the accretion of independently derived genetic elements. It is now evident that modern genomes are remarkably fluid in their composition and that they have evolved, in part, by the incorporation and shuffling of previously independent genomes.

From what is known about modern genomes, it seems that the eukaryotic cell nucleus is significantly different in its organization from that of either the eubacteria or the archaebacteria. Although lateral gene transfer probably has had a prominent role in the evolution of all genomes, the eukaryotic cell nucleus seems particularly susceptible to the acquisition of genes through endosymbiosis. For example, there is ample evidence for the transfer of genes from mitochondrial and chloroplast genomes to the cell nucleus.

OBJECTIVE 4: *To elucidate the organization and interrelationships of phylogenetically diverse genomes.*

An earlier report of this committee recommended research on the sequences of monomers in information-bearing polymers (SSB, 1981). Now, macrosequencing projects involving large eukaryotic genomes seem inevitable; the technology is at hand for the detailed mapping of bacterial genomes (the entire *Escherichia coli* genomic DNA sequence will soon be available); and several mitochondrial and chloroplast genome sequences have been published. In view of the substantial contributions of comparative studies

of single genes, it is anticipated that insight will come from comparative studies of whole genomes. Data of this type provide the inference of the evolution of genome organization and direct insight into important phenomena such as the development of novel pathways and interrelationships between protein families.

It is clear that a major commitment for genome analysis will require support from many federal agencies besides NASA. However, important aspects of this major undertaking are within the purview of NASA's program in planetary biology and chemical evolution: for example, analysis of sequence data from the standpoint of the essential elements of genome structure and its fluidity and the implications of such studies for the origin of life. It will thus be necessary for NASA to establish active liaison with other concerned federal agencies (NIH, NSF, DOE) that are developing programs in genome analysis; seeking ways in which NASA expertise can interdigitate fruitfully. Such interactions might involve developing theoretical models that bear on genome expression, developing robotics for gene mapping and sequencing, and providing sound experience in data-processing analysis.

5

The Evolution of Cellular and Multicellular Life

INTRODUCTION

Our perspective on biological evolution is that it is a cosmic phenomenon, born of galactic and solar-system processes and influencing the further development of planetary surfaces where it occurs. Although traditional studies of terrestrial evolution have considered biology to be a system apart from and, in many respects, independent of the physical Earth on which it resides, increasing evidence compels us to reject this view in favor of a concept of life as intimately linked with the crust, sediments, oceans, and atmosphere, through an interacting series of biogeochemical cycles. Indeed, life is an outgrowth of solar-system and planetary evolution.

The characteristic feature of the evolutionary process is its dependence on context. The unfolding of terrestrial life must be understood as contingent on the particular course of this planet's development. Both the origins of life on Earth and its subsequent evolution have been influenced strongly by events in the evolution of the physical Earth and by extraterrestrial phenomena (such as bolide bombardment) that have impinged the Earth throughout its history. To understand the evolution of terrestrial life, a much more *integrated* understanding of Earth's biological and physical history must be developed. Such an understanding is requisite to determining the extent to which the course of biological evolution on Earth can be regarded as a general feature of life and, thereby, likely to be representative of life throughout the universe.

The earlier phases of evolution are most likely to share common characteristics on different planets. As biological systems on Earth became more complex, they came to have a greater influence on their own evolutionary development and that of the planetary surface as well. The major determi-

nants of early evolutionary change on Earth, however, were changes in the physical environment. Hence, although the course of evolution of more complex organisms elsewhere in the universe is difficult to predict using Earth as a model, the major transition from physical to biological evolution of organic matter, similar to that thought to have occurred on Earth, is expected to characterize all planets whose early physical evolution is comparable to that of our own.

In recognition of the need for an integrated approach to evolutionary problems, another report of this committee (SSB, 1981) recommended the following: "It is essential that data obtained using molecular methods with live organisms be evaluated in the context of the sedimentary rock record." Since the preparation of that report, methodological progress has been so substantial that it has become possible, indeed necessary, to expand and refine the recommendations of that report.

Integration of the Earth's biological and physical history now seems to be attainable: molecular approaches permit the inference of evolutionary relationships for all extant life. This advance is complemented by advances in electron microscopy, making it possible to define ultrastructural phenotypes and trace their development in microorganisms. Renewed exploration of diversity in prokaryotic metabolism, spurred by the recognition of the archaebacteria as a distinct prokaryotic kingdom, has demonstrated the existence of evolutionarily important bacterial metabolisms that were unknown a decade ago. Knowledge of the early Earth has expanded in concert with this biological progress and, for the first time, evidence has accumulated that forces us to consider the role of extraterrestrial factors in determining patterns of terrestrial evolution.

With this in mind, the committee has articulated four goals for future research on the evolution of cellular and multicellular life. These four goals, which are components of a larger primary goal of understanding the interrelationships between physical and biological evolution on planetary surfaces, seem appropriate for NASA sponsorship and coordination. These goals and objectives have not been prioritized because all are necessary for the integrated understanding to which we aspire. Balance, rather than prioritization, is the key to a successful research program in cellular and multicellular evolution.

In delineating the specific objectives of these goals and the recommended research, it is important to note the critical role of NASA in coordinating and catalyzing the interdisciplinary study that will be necessary. No other agency is capable of providing the conceptual or intellectual umbrella for the evolutionary research advocated in this chapter.

The goals defining a strategy for research on cellular and multicellular life, together with their component objectives, are described below.

GOAL 1: *To develop a universal understanding of the temporal sequence and evolutionary relationships of life on Earth.*

Recent molecular data support the view that all extant (living) organisms on Earth descend from a common ancestor. At this time, there are three principal lines of evolutionary descent from this common ancestor, namely, the three major phylogenetic groups: the archaebacteria, the eubacteria, and the eukaryotes. Evolutionary relationships within and among these groups can be examined by a variety of biological, paleobiological, and geological means. Traditionally, evolutionary relatedness has been assessed by comparison of phenotypic characters. This system of inquiry has worked reasonably well for plants and animals, but it has been of only limited value in defining relationships among fungal, protistan, and prokaryotic microorganisms because of their simple morphology (phenotype) and lack of fossil preservation. The committee suggests that a different combination of insights (items 1 to 3 below) will provide a markedly improved understanding of archaebacterial, eubacterial, and eukaryotic evolution:

1. *Molecular phylogeny:* All living organisms contain an extensive record of their own phylogenetic history. Nucleic acid sequencing technology now provides ready access to much of this biologically incorporated history. From sequence comparisons (for homologous functions), quantitative evolutionary relationships can be inferred, and these serve as conceptual frameworks within which to relate phenotypes and their temporal evolution, as well as the ecological and geological conditions surrounding the evolutionary process.

2. *The characterization of phenotypes:* The characterization of phenotypes provides an independent set of biological data that can indicate pathways and possible causes of morphological and/or biochemical evolution. Among prokaryotes (archaebacteria and eubacteria), many of the most important characters currently used in phenotypic characterization are metabolic, whereas in eukaryotic protists they are predominantly ultrastructural. In plants, animals, and fungi, these are largely anatomical and morphological. Consideration of phenotypes and ecology in the context of molecularly derived phylogenetic relationships permits the generation of hypotheses concerning the conditions under which evolutionary innovations arose.

3. *Paleontological and geological record:* The paleontological and geological record provides a testing ground for these hypotheses and can further illuminate the causes of environmental changes or occurrences associated with significant evolutionary events. Paleontology traces the actual course of terrestrial evolution, indicating the sequence of appearances and disappearances of preservable phenotypes and placing constraints on the timing of evolutionary origins. Equally important, the analysis of sedimen-

TABLE 5.1 Information Content of a Precambrian Fossiliferous Rock

1.	Physical environment of deposition
	Bedding and sedimentary structures
2.	Chemical environments of deposition and diagenesis
	Petrology and geochemistry
3.	Biota living in, or transported to, the site of deposition (incomplete sampling)
	Micropaleontology
	Chemical indicators of metabolism (e.g., carbon isotopes of carbonate and organic matter; sulfur isotopes of pyrite and sulfate; molecular fossils)
	Traces of microbial activity (stromatolites, microphytolites, oncolites)
4.	Chemical indices of global tectonic and biogeochemical systems
	Strontium isotopic ratios
	Carbon isotopic ratios
	Sulfur isotopic ratios
	Rare earth element abundances
	Oxidation state of weathered surfaces

tary rock sequences in which fossils are found provides important clues to the environmental evolution of the Earth's surface. A given sedimentary sample contains information on the sedimentary, tectonic, and geochemical environments in which organisms lived and/or were buried. It also records many features of its subsequent diagenetic history and may contain isotopic indices to the pulse of biochemical cycles and tectonic activity (see Table 5.1). From the examination of samples along environmental gradients in a single time plane come paleoenvironmental and paleogeographic reconstructions, as well as the determination of paleoecological distributions of coexisting organisms. Analyses of time sequences of samples (normalized for environment) provide the geological evidence for both biological and physical evolution and the means of relating the two.

OBJECTIVE: *To study a wide variety of organisms by using the techniques of molecular phylogeny and biochemical and morphological characterization.*

A decade ago biologists regarded our understanding of eukaryotic phylogeny as fairly complete, whereas evolutionary relationships among bacteria were considered unknown quantities. Today bacterial relationships at higher taxonomic levels are regarded as well known, whereas increasing data have exposed our ignorance about eukaryotic phylogeny. The committee believes that the time is ripe for concerted effort on fundamental questions of eukaryotic cell evolution.

Speculation has long focused on certain bacterial characters of the major

organelles—the mitochondria and chloroplasts. It is now abundantly clear, from molecular phylogenetic comparisons—particularly of rRNAs—that mitochondria and chloroplasts are derived from specific eubacterial groups. However, there are many morphologically and biochemically distinct versions of these organelles, only a few of which have been inspected in terms of molecular phylogeny. Questions therefore arise as to whether mitochondria and chloroplasts each arose only once or many times. Moreover, it is now clear that substantial genetic exchange has occurred between mitochondria and chloroplasts and their host eukaryote nuclei. The mechanisms and rationale for the genome mixing are not understood, but the occurrence has important implications for the evolution of eukaryotic cells. The continuing molecular investigations of eukaryote and prokaryote diversity should include analysis of the organelles as well, so that their origins and coevolution with host cells can be evaluated.

Nucleated organisms have been thought to be descendants of forms related to present-day prokaryotes and, hence, viewed as more recently evolved taxa. However, the emerging phylogenetic framework inferred from comparisons of small-subunit (~16S) RNAs shows that the sequence diversity of eukaryotic RNAs eclipses that of archaebacteria or eubacteria. Such a finding is consistent with the hypothesis that the eukaryotic nuclear line of descent represents an extremely old superkingdom, derived directly from the "progenote" rather than from prokaryotes belonging to the other two superkingdoms. The eubacterial line of descent, however, contributed the two major organelles, the mitochondria and the chloroplasts. The breadth of genotypic and biochemical diversity of the eukaryotes observed thus far is represented by members of the Protista; the microsporidians, euglenoids, and trypanosomatids have been identified as particularly early branches on the eukaryotic tree. Other eukaryotic divisions—especially plants, animals, and fungi—appear to have arisen nearly simultaneously during a relatively recent radiation.

Despite these revelations, the understanding of eukaryotic evolution is limited by the small number of taxa examined to date and by the inability to bring genotypic phylogenies into juxtaposition with relationships inferred from comparisons of phenotypes and the fossil record. Several other protistan groups, including the dinoflagellates and oxymonads, may represent additional early branches in the eukaryotic line of descent, but comparative morphology cannot be solely relied upon for inferring branching order. The uncorroborated assignment of primitive status to particular characters is frequently difficult to determine. Recent progress in ultrastructural research, coupled with molecular phylogeny, promises to clarify these issues. Notable successes include the new phylogeny of green algae, which differs appreciably from traditional phylogenies, and which greatly clarifies the evolutionary history of this group and its descendants, the land plants.

Metabolic Diversity

Molecular data show that the main phylogenetic diversity of life on Earth is in the microbial world, both prokaryote and eukaryote. Traditional microbiological investigations have relied on laboratory cultivation for the characterization of organisms. Yet, it is known that many, perhaps most, organisms in natural microbial populations have not been, and perhaps cannot be, maintained as pure laboratory cultures. This is attested to by the continued discovery of novel organisms, the abundant occurrence of symbiotic associations, and the recognition of large, so far uncultivated populations of organisms. An outstanding example of the latter is the marine planktonic microbiota, which was long considered sparse on the basis of laboratory cultivation. Over the past decade, however, direct microscopic investigations have revealed an abundance of marine "picoplankton" (organisms less than 2 μm in diameter), including eukaryotes, prokaryotes, phototrophs, and heterotrophs. Cultivation attempts have repeatedly failed to retrieve representative forms; thus, a potentially major influence on the biosphere remains uncharacterized. Methods for analyzing phylogenetic and quantitative aspects of natural microbial populations, without laboratory cultivation, are now available. These methods use RNA gene cloning and sequencing approaches. The expansion of such approaches to many populations and environments should be encouraged so that a full representation of phylogenetic diversity may be achieved.

It is of critical importance to the understanding of eukaryotic evolution that the sequence sampling be integrated with expanded studies of the ultrastructure, ultrastructural development, and biochemistry of sequenced taxa. A fuller understanding of eukaryotic evolution is necessary if data from this superkingdom are to be pooled with those from eubacteria and archaebacteria to make informed inferences about the nature of the "progenote."

Just as electron microscopic studies have revealed a hitherto unappreciated diversity of eukaryotic phenotypes in terms of ultrastructure, so too have recent biochemical studies of prokaryotes revealed a metabolic diversity significantly broader than previously thought. The isolation and characterization of microorganisms having previously unknown metabolic capabilities (especially among the archaebacteria, cyanobacteria, and sulfur-reducing prokaryotes) have markedly revised some of the traditional "metabolic dogma." The discovery of these metabolic potentials has allowed the expansion of our understanding of modern ecosystems, both aerobic and anaerobic, and thus has enlarged the cast of characters available for modeling ancient ecosystems. The phylogenetic characterization of these new organisms will provide further insights into the evolution of metabolism and may, in conjunction with geological data, allow scientists to constrain the time of origin of certain metabolic phenotypes.

Through such coupled phenotypic, molecular, and geological studies it

may be possible to resolve more satisfactorily the succession of ecosystems that have characterized our planet through history. Limiting steps in such ecosystem reconstruction are the isolation and characterization of organisms whose unique metabolic capabilities allow them to persist in extreme environments.

For example, although seemingly unusual in the context of today's environments, recently discovered thermophilic, anaerobic, sulfur-dependent archaebacteria may provide important clues to the nature of the early biosphere.

The expanding repertoire of prokaryotic metabolisms can be used to guide further research. For example, among presently known archaebacteria, many—but not all—of the complementary metabolisms needed to complete biogeochemical cycles are known to exist. The question of whether archaebacteria could maintain element cycles in the absence of eubacteria is especially important for an understanding of biological diversification on the early Earth.

GOAL 2: *To determine the properties of the universal ancestor of extant organisms.*

Understanding the universal ancestor of life on Earth is critical to understanding evolution on this planet. Because of the general evolutionary principle of descent with modification, the nature of the earliest biological entities constrained subsequent evolution and, in the attempt to link biological to prebiological chemical evolution, also constrains our views of how life arose.

The earliest life forms on Earth must have been far simpler than any organism now alive. Although these primordial organisms are extinct, clues to their genetic organization, metabolic capabilities, and other phenotypic characteristics are retained in the biological traits of unicellular organisms that represent early branchings in each of the primary lines of descent. By comparing features common to these evolutionary lineages, it may be possible to infer the phenotypes of the earliest organisms; it is probable that features common to early branching groups will reflect features possessed by their common ancestors. As mentioned above, studies of molecular phylogeny have brought the universal phylogenetic "tree" within reach. In addition to providing the starting point for inquiries into the course of biological evolution within the three primary kingdoms, this set of phylogenetic relationships provides a framework for asking about life's earliest history before segregation of the three extant lineages.

OBJECTIVE: *To root the universal phylogenetic tree.*

Our understanding of the ancestor of all extant life rests heavily upon knowing the root of the universal "tree" of phylogenetic relationships. One needs to know, for example, whether the archaebacteria and eubacteria are

specifically related to one another to the exclusion of the eukaryotes. One also needs to know whether the archaebacteria are more primitive in phenotype than the other two major types. Although the position of the root of the universal tree must be known to answer both questions, a partial answer to the second can be given in the absence of this knowledge.

Although phylogenetic relationships are customarily rooted by invoking known outgroup species, that is not an option for the tree that encompasses all life. However, this does not mean that the root of the universal tree is unknowable. Another way to determine the rooting is through comparisons among sequences of genes that have doubled and functionally separated while still in the universal ancestry state, provided that their sequences have retained a sufficient degree of similarity. Thus, the search for gene families overlaps the problem of rooting the universal tree.

The universal ancestor, the so-called progenote, is considered to have been a distinct entity ancestral to, but qualitatively different from and more rudimentary than, any of its daughter lineages. It was sufficiently primitive that its capacity to transmit information from genotype to phenotype would have been more limited than that of its descendants; that is, translation at this stage was presumably more inaccurate (prone to errors) than in later organisms (see also Chapter 4).

Four salient characteristics follow from such translational inaccuracies: (1) proteins at this time would not have been typical of proteins seen in cells today (e.g., they were probably smaller than modern proteins if they were accurate translations of genetic messages); (2) the genes the organism carried would have been fewer in number than prokaryotes now carry; (3) genes at this stage were perhaps not arranged in large linear arrays (genomes); rather, they may have been physically separate entities, probably composed of RNA, not DNA; and (4) in all respects the level of biological specificity for the progenote was presumably lower than now exists.

As living systems evolved from this state to those represented by the three major kingdoms, they would have evolved a more varied set of genes coding for proteins of ever-increasing variety and specificity. Traces of this evolution are preserved in gene families of living organisms. For this reason, therefore, the committee recommends as a principal objective of research the recognition and evolutionary evaluation of gene families.

GOAL 3: *To understand what factors drive the biosphere.*

As emphasized in an earlier report of this committee (SSB, 1981), biological evolution has not proceeded independently of planetary evolution, nor has it been immune to influences from Earth's cosmic environment. The fossil record documents numerous episodes of evolutionary radiation; molecular phylogeny also suggests that evolution occurred in bursts. Why does evolutionary history appear to have this pattern? Traditional explana-

tions have stressed the evolution of new phenotypic characters (innovations) that confer the ability to utilize an underexploited resource or to compete for ecologic success, and some radiations may indeed represent such phenomena. However, many of life's major radiations appear to be related to environmental changes that presented new opportunities or removed long-standing constraints. Mammals, for example, radiated early in the Tertiary period not so much because of any innovation on their part as because the previous ecological dominants in many terrestrial niches, the dinosaurs, became extinct at the close of the Cretaceous period. Among eubacteria, evidence begins to suggest that oxygen utilization arose at about the same time in different lineages, probably during the late Archean to Early Proterozoic, which geochemical markers indicate was a time of rising atmospheric oxygen tensions.

An interesting example highlights these close interrelationships among biological, tectonic, and environmental changes. Approximately 600 million years ago, after more than 3 billion years of microbial evolution, macroscopic animals radiated over the face of the Earth. Why did this evolutionary burst occur 600 million years ago rather than 1 billion years ago or some other time? Biologists have long stressed that animal life requires certain minimum oxygen tensions to support exercise metabolism, to ensure the diffusion of oxygen to internal cells in organisms having multiple cell layers, and to complete certain biochemical reactions. Recent geochemical evidence suggests that just prior to the observed radiation of the Ediacaran fauna, significant amounts of oxygen may have accumulated in the atmosphere—a consequence of abnormally high rates of organic carbon burial. The anomalous carbon burial, in turn, correlates well with sedimentary and geochemical evidence for continental breakup and the opening of Late Precambrian ocean basins and suggests a relationship similar to that documented for the Permian through Early Cretaceous periods, when the breakup of Pangaea promoted the accumulation of economically important concentrations of organic matter. The model that is emerging involves a tectonic event, its biogeochemical consequences, and attendant changes in the composition of the atmosphere that remove an environmental constraint to the evolution of tissue-grade multicellularity. This model and others like it must be tested and refined in light of new geological and geochemical data, but they underscore the point that biological evolution cannot be understood outside of the context of physical Earth history, and vice versa.

OBJECTIVE 1: *To integrate the biological accounting of the Earth's historical development with that obtained from studies of the geological record.*

Substantial progress in unraveling the environmental evolution of our planet will require detailed sedimentological, stratigraphic, paleontological,

and geochemical analyses of well-preserved sedimentary basins, particularly those of Archean and Proterozoic age. Global syntheses are only as useful as the data that go into them, and at present the base of carefully collected and analyzed data is insufficient to tie the geological record to the biological record in the way the committee believes is possible.

OBJECTIVE 2: *To determine the influence of Earth's cosmic environment on evolution.*

In 1985, NASA published an important workshop report: *The Evolution of Complex and Higher Organisms* (ECHO). The object of the ECHO report was to explore the last 600 million years of biological evolution on Earth in the context of the Earth's cosmic environment. The report concluded with the recommendation that NASA initiate a new study program designed to link existing programs in planetary biology and thereby to include in NASA's overall research effort the important evolutionary events that took place in the interval between the appearance of multicellular life and the evolution of man.

During the last 600 million years of Earth history (the Phanerozoic eon), animals, plants, and fungi have diversified on this planet, initially in the oceans and then on land. Complex social behavior has arisen in several phyla and technology in one. In short, the modern biota has taken shape during the last 15 percent of the Earth's development. This evolution was once seen as an orderly progression from simple to complex, with more complex organisms being selected in favor of their more primitive ancestors. The seeming inevitability of this progression was used as a model for the evolution of life in any planetary system. The evolution of life on Earth was also seen as operating in a closed system not significantly influenced by events and processes in space.

The general view of the evolution of advanced life now appears to be grossly oversimplified, to the point of being essentially wrong. The fossils preserved in the Phanerozoic record show evolutionary change (sometimes gradual, sometimes spasmodic), but they do *not* conform to predictions of linear models of progressive evolution. There is no evidence, for example, that the extinct trilobites of the Paleozoic era were simpler or less specialized than their modern counterparts. Tropical reefs have been in existence and have flourished throughout most of the Phanerozoic, yet the framework builders of these reefs have varied markedly through time; the coral reef of modern seas is just the current version of a recurrent ecosystem. There is no reason, from first principles, to argue that mammals should have appeared when and how they did. Humanoid intelligence evolved only once, but there is no reason it could not have evolved several times in separate lineages—or not at all.

It is becoming increasingly clear that the Earth's cosmic environment has

important influences on biological evolution. The history of life on Earth can no longer be seen as operating in a closed system. During the Earth's history, the Sun's luminosity has increased about 30 percent, day length has increased, ocean tides have decreased, the planet has been bombarded by comets and asteroids, and the solar system has undoubtedly been influenced by the gravitational effects of randomly passing field stars and by occasional supernovae. Phanerozoic time has included three galactic years, and the Earth has passed through the plane of the galaxy perhaps 20 times. The ECHO report considered these and other effects while focusing on two questions. (1) Do events and processes in our cosmic environment leave recognizable signatures in rock or fossil records? (2) How have these events and processes influenced the evolution of advanced life? On the one hand, innovative geochemical analyses will be necessary to constrain better the history of atmospheric oxygen or ocean chemistry. On the other hand, better constraints on temperature history, solar radiation, and the like may require information from improved models of solar-system evolution based on comparative planetology and observations of the Sun.

There have recently been a number of striking research successes in relating past global biology to solar-system or galactic influences. Work with the marine micropaleontology of the past 700,000 years has shown rather decisively that cycles of climatic change, including the several pulses of continental glaciation, can be tied directly to Milankovich cycles of orbital change in the Earth-Moon-Sun system. This work is being extended to recognition of Milankovich cycles deeper in the geologic past. It also shows promise of having important implications for problems of global climate and predictions of future climatic change.

Another success is the discovery of geochemical and geophysical evidence for a major comet or asteroid impact 65 million years ago, at the time of the terminal Cretaceous mass extinction. Although there is still considerable controversy over the role of this impact in the mass extinction of dinosaurs and other organisms, the work has dramatically increased the attention being paid to large-body impacts as influences on past life.

At the very least, research on the possible effects of large-body impacts has sensitized the scientific community to think more in terms of cosmic influences on Earth systems. Current estimates of comet and asteroid impact rates call for about 12 impacts of objects 10 km or larger, and up to 3600 impacts of objects 1 km or larger, during the Phanerozoic. Although the environmental consequences of these impacts are still poorly known, there is an intriguing possibility that the large number of smaller impacts has been responsible for the lesser regional extinctions that punctuate the history of life.

It seems likely that research to date has barely scratched the surface of a new and exciting field of science. Regular and irregular events in space

may be crucial elements in our evolutionary system. In fact, arguments can be made that in the absence of this sort of *physical disturbance*, biological evolution would have reached steady state hundreds of millions of years ago, thereby preventing the evolution of advanced life as we know it. The most likely scenario is one in which externally induced environmental shocks eliminated dominant organisms at certain times, thus accommodating the innovations so important to long-term evolution.

Research on the evolution of advanced life may also have direct benefits in other aspects of space science. For example, if solar-system and galactic history can be documented from the geologic and fossil records, astronomy will have, for the first time, a means of empirical verification of time-dependent processes that can otherwise be treated only theoretically.

The foregoing discussion must remain open ended because of the fledgling nature of the field. Emphasis is given to Milankovich cycles and large-body impacts because these are areas in which there has been some preliminary success; however, totally different aspects of the cosmic and planetary environment may prove to be important to the global biology of the past, present, and future. To improve techniques for the quantitative understanding of environmental conditions on the early Earth, NASA should continue to take the intellectual lead in fostering interdisciplinary research and communication among scientists having disparate specialties. It is particularly important that NASA encourage improved communication among molecular or evolutionary biologists, paleontologists, Precambrian geologists, and planetary modelers by sponsoring workshops, symposia, and innovative interdisciplinary research projects.

GOAL 4: *To generalize our understanding of environmental and early cellular evolution on Earth by comparative studies of Mars.*

Because no other planet in the solar system appears to harbor living systems, most scientists have assumed that any comparative study of biologically active planets will necessarily involve other solar systems at great distance from the Earth. This may be true if only present planetary surfaces are considered, but if we look at the geological records of ancient planetary conditions, this assumption may prove to be wrong. The case for exobiological input into Mars sample return missions has been made by the SSB Task Groups on Planetary and Lunar Exploration (SSB, 1988b, pp. 99–106) and Life Sciences (SSB, 1988a, pp. 47–51). This committee simply underscores the importance of exobiological research in any and all future Mars missions.

OBJECTIVE: *To investigate the sedimentary record of Mars which, because of similarities to Earth in its early stages of planetary development, offers a unique opportunity to expand and generalize our understanding of environmental and early cellular evolution.*

According to the logic developed at the beginning of this chapter, if biological processes arise from physical ones under a given set of physical conditions, and if early stages of evolution on different planets appear, in principle, to be more likely comparable than later stages, then there are compelling intellectual reasons to conduct detailed investigations of Mars for possible evidence of prebiotic and early biological evolution. For these purposes, studies on Mars should concentrate on early supracrustal successions and include well-designed site and sample selection strategies that maximize the potential for evaluating the environmental and possible early cellular evidence of evolution on Mars.

PRIORITY CONSIDERATIONS

This chapter has stressed the goal of developing an integrated understanding of the evolution of life on this planet, as well as the exciting prospect of testing the universality of early events in this history through the geochemical and paleontological examination of ancient supracrustal rocks from Mars. The research advocated here is highly interdisciplinary, with the consequence that program balance must take precedence over strict prioritization. Nevertheless, the committee can highlight three principal components of any successful research program aimed at understanding the course of evolution on our planet:

1. development of robust phylogenies relating living microorganisms, through the comparison of sequences in informational macromolecules, especially small subunit ribosomal RNAs;
2. elucidation of the biochemical and ultrastructural characters of microorganisms in order to relate patterns of phenotypic diversity to phylogeny; and
3. development of improved data on the biological and physical development of the Earth through careful sedimentological, geochemical, and paleontological analysis of ancient sedimentary basins. Geological research should be aimed not only at the elucidation of environmental evolution, but also at understanding the cosmic influences on terrestrial environments and evolution.

As discussed in the final chapter of this report, much of the planning for Mars sample return missions will be spearheaded by groups outside of the exobiology research community; however, the committee views the participation of exobiologists in mission planning and execution as essential. It is difficult to imagine more exciting and fundamental questions that can be addressed by such a mission than those concerning the early surficial environment and the possibility of chemical or even biological evolution on the early surface of our neighboring planet.

Some areas of exobiological research are supported by other agencies in addition to NASA, especially NSF. NASA's continuing support is critical, however, because only it can provide the programmatic integration that promotes the necessary cross-fertilization of the various disciplines relevant to exobiology. Given the structure of NSF, the search for interstellar molecules, Archean geochemistry, and microbial metabolism are necessarily viewed as unrelated topics. Only under NASA's aegis are they integrated as components of a single research effort. This fact cannot be overemphasized.

6

Search for Life Outside the Solar System

INTRODUCTION

Life as we know it is a planetary phenomenon: its origin appears to have required interactions among liquid water, a gaseous atmosphere, and minerals provided by a solid planetary surface. The energy required to produce the appropriate chemical reactions was available from solar ultraviolet light, bombardment by charged particles, meteoritic impacts, local volcanism, hydrothermal vents, lightning discharges, coronal discharge, and even acoustic shocks.

A nearly circular orbit about a stable star promotes fairly uniform conditions for the billions of years required (at least on Earth) for life to evolve from single cells with no nuclei to multicelled intelligent organisms. The evolution and dispersion of life on Earth have radically altered the surface, oceans, and atmosphere of this planet in ways that are discernible from a remote observational vantage point. During the past 1.5 to 2 billion years, a distant observer would have found presumptive evidence for life on Earth in the oxygen-rich nonequilibrium chemistry of the Earth's atmosphere. More recently, the microwave signals generated by human technology could provide that same remote observer with circumstantial evidence for the existence of some form of intelligence on the planet Earth.

These two examples of life detection should apply to other planets as well. Isolating the light or thermal radiation of a distant planet from the brilliance of its star would enable us to examine the spectrum of the planet and search for chemical evidence of the existence of life. This evidence would take the form of some massive departure from chemical equilibrium, a large amount of free oxygen being the most obvious example and probably the most observationally traceable. However, the detection of trace gases such as CH_4, NH_3, N_2O (nitrous oxide), and CS_2 (carbon disulfide) in

excess of the amounts predicted by chemical equilibrium and plausible nonequilibrium sources might also provide presumptive evidence for life if the 4- to 11-μm region of the spectrum could be accessed. Detection of signals generated by an extraterrestrial technology would be even more compelling evidence that life is not uniquely confined to Earth. (Although searches for such signals have become known as SETI [the search for extraterrestrial intelligence], in reality such searches could detect only those intelligent forms that utilize an electromagnetic technology.) In this chapter, both of these approaches to the detection of life outside the solar system are discussed.

GOAL: *To understand the nature and distribution of life in the universe.*

The underlying scientific goal in searching for life beyond the solar system is the same as the goal of the Viking biology experiments on Mars or the study of astrophysical influences on the evolution of life on the planet Earth.

As described in previous chapters, there are compelling reasons to look for evidence of the origin of life on Mars during a more clement epoch of that planet's history. On the other hand, the prospects for detecting extant life on Mars seem remote. To find such life, our vision must expand beyond the realm of the known planets and moons.

Recent strategy reports from this committee (SSB, 1981, 1986) emphasized the dynamic and complex interactions between life and its terrestrial environment. Those reports focused on the opportunities afforded by suitable airborne and orbital platforms for the study of the terrestrial biosphere as a single, complex—but closely coupled—system. Now it is time to extend this perspective to other planets and satellites in other planetary systems. The same kind of evidence that reveals the presence of life on Earth can, in time, be sought in other planetary systems. If the search is successful, it will mark the beginning of a new science. It will then be possible to examine life on Earth as just one of several examples of a remarkable property of matter, rather than the only example. This challenge was recognized by the authors of the 1981 SSB report: "The emergence of complex societies capable of extraterrestrial communication is an evolutionary biological phenomenon. Thus, the problems of the search for, and attempt to communicate with, extraterrestrial life lie at least in part within the province of planetary biology and chemical evolution."

APPROACHES TO THE DETECTION OF LIFE OUTSIDE THE SOLAR SYSTEM

If we are to attempt to sense the impact of life on distant planets from this remote vantage point, those planets must first be located. At present,

there is no unambiguous evidence of the existence of an extrasolar planetary system, although there are many tantalizing clues.

The detection of even a single example of an extrasolar planet that has been modified by the evolution of life would have extraordinarily profound consequences. It would then be possible to bring to bear the full power of the scientific method in extracting laws of nature from several examples of the same phenomenon. Despite its extraordinary diversity, life on Earth offers just a single example from which it is impossible to generalize to other systems. To escape from this dilemma, those other systems must be found in order to achieve the fundamental goal of understanding the distribution of life in the universe.

The basic techniques for detecting extrasolar planets are well understood (a detailed discussion of this subject is given in reports of the SSB, 1988a,b). Individual planets, once formed, will have a number of perturbing effects on the motion and apparent brightness of their host star, but these effects will be very small and will require extreme measurement accuracy. For example, the accuracy required to detect Jupiter-mass planets around the nearest stars has been achieved—with heroic efforts—during the past two decades. Recent technological advances now allow previous accuracies to be obtained more rapidly and make additional detection schemes feasible. Planets with the mass of Neptune may become detectable within the decade, but the detection of Earth-mass planets will require dedicated space-based systems, not yet approved by any funding agency. It is appropriate for the purposes of this report to consider what systems are available now, which are planned for the immediate future, and, especially, what must be studied to ensure that instruments of significantly improved capability become available to the next generation of planet seekers. These instruments must be systematically and exhaustively employed for long periods of time if a census of even the nearest stars is to provide a basic understanding of the frequency of planetary systems. Furthermore, we must be able to extend what is learned from studies of nearby planetary systems to the more distant stars around which we cannot hope to detect planets by these simple techniques.

Programs to search for other planets have been endorsed repeatedly. These endorsements by astrophysicists and planetary scientists are concurred in by scientists interested in studying the origin and evolution of life. In this regard, it should be noted that the desire of exobiologists to examine spectroscopically the global chemistry of a distant planet imposes the most extreme instrumental requirements.

In parallel with this search for passive evidence of the existence of life beyond the solar system, a different kind of search can be carried out: that is, the search for evidence of technologically advanced civilizations. The unambiguous detection of an extrasolar technology would have profound implications. Not only would we know that life in the universe is not

unique to the planet Earth, but we could contemplate the possibility of communicating with, and learning from, the intelligent life that created the detected technology. It is conceivable that the distribution of life in the universe could come to be understood in the larger context of the evolution of the cosmos. These possibilities have previously been endorsed by the National Research Council (1972, 1982).

Since the 1940s, there has been a rapid growth in the techniques and technology of communications and radio astronomy that can improve the chances of detecting signals at great distances. These tools have not yet been brought to bear SETI in a systematic way. It is now possible, by using state-of-the-art instrumentation, to expand the search domain for extraterrestrial signals far beyond anything that has been done to date. These searches for deliberately generated signals should be complemented by searches for other indirect manifestations of a distant technology.

Although the two approaches to searching for life beyond the solar system can provide very useful inputs to each other, they may be pursued independently and simultaneously at a pace set by the rate of maturation of the requisite technologies. NASA is the leading agency in the development of most, if not all, of the necessary instrumentation. Furthermore, NASA is the agency responsible for providing the orbital platforms required by some of the observational techniques (discussed below). The readiness of some of the requisite technology and the concurrent development of orbital astronomical facilities invite rapid implementation of search programs utilizing these capabilities.

SCIENTIFIC OBJECTIVES

To achieve an understanding of the nature and distribution of life in the universe, a number of discrete scientific objectives must be carried to completion. In many cases, these objectives overlap those already enunciated by the Astrophysics and Solar System Exploration program offices within NASA. However, it is important to remember that the desire of exobiologists to study both the nature and the distribution of life in other potential habitats is likely to place more stringent technical requirements on the relevant instrumentation than demanded by other objectives.

It is necessary to ask, in a cosmic context, how unique are this solar system, the Earth, and terrestrial life? The precise mechanisms that led to the formation of our solar system, with its small, dense inner planets and its more distant gas giants, are the subject of much debate. Debatable as well is the time scale over which these processes occurred. Consistent with current theories of planetary formation, there does not seem to be anything unique about the protosolar nebula; other nebulae around other stars should also form planets by the same methods, whatever they are. Comparative

studies of protostellar nebulae currently in the process of collapse and, perhaps, planet formation could provide a bound on the length of the process, as well as an estimate of the mass ratio between the flattened nebula and the centrally condensed protostar. The latter quantity is the key to distinguishing among current models of planetary formation. There are a number of Earth-orbital telescopes for infrared and submillimeter observations under design, or in the planning stage, but as currently conceived, none will provide the resolution of 0.01 to 0.1 arc sec necessary to observe dimensions corresponding to our planetary system within distant protostellar nebulae. The recent study *Space Science in the Twenty-First Century* (SSB, 1988b) noted this same deficiency and recommended that advanced technology programs be pursued to achieve this accuracy in future systems.

Perhaps the closest we can get to the process of planet formation is to study the extended disks of dust and gas surrounding some young stars that have just reached the main sequence. These stars were discovered in the analysis of the IRAS four-color data. A significant infrared excess in the 60-μm band has been correlated with the existence of a dusty disk component circling the distant star. These disks are typically much larger than our solar system. Whether there is a selection effect favoring large disks, whether the size of the disk is determined by the age of the star alone, and whether planets have formed, are about to form, or have failed to form in these large disks are questions whose answers are still unknown. These are certain to be topics for thorough investigation in the coming years. Studies of these disks and their frequency of occurrence have not yet produced any general agreement among theorists as to how planets form.

During the coming decade it may not be possible to determine observationally the processes by which other planetary systems (and by extension our own) formed. It should, however, be possible to verify observationally that other planetary systems have indeed formed. The unambiguous detection of the first extrasolar planet will validate the hypothesis that planetary formation is not uniquely related to the Sun.

OBJECTIVE 1: *To determine the frequency and morphology of nearby planetary systems.*

For the purposes of exobiological understanding, a significant planetary census will be required. Only this can provide a meaningful estimate of the frequency of occurrence of terrestrial-mass planets at orbital distances from the primary star that are suitable for the maintenance of surface temperatures amenable to life.

A survey of nearby stars must be made initially to determine the frequency of planetary-system formation in our local galactic neighborhood. This survey must be augmented with a study of distant protoplanetary disks and protostellar nebulae to allow for extrapolation of the frequency of

planetary-system formation throughout the galaxy. Once detected, the distribution of extrasolar planet masses as a function of the distance from the parent star (location in the protostellar accretion disk) must be determined and correlated with stellar type to better understand the processes that control the formation of planets and the role of the central condensed protostar. From observations of protostellar nebulae and early stellar disk systems, an evolutionary sequence of events and time scales should be developed to predict the rate at which planets are formed within the Milky Way. The sensitivity of available instrumentation will undoubtedly dictate that these surveys proceed in a stepwise fashion. The detection or (equally significant) nondetection of Jupiter-mass planets in the vicinity of the nearest few stars and the study of the largest dust disks around young stars will come first. These should be followed by the search for lower-mass planets (down to terrestrial size). Investigation of protoplanetary formation in progress around distant protostars can commence whenever instruments of sufficient angular resolution permit. To implement these investigations properly, advanced technology studies are needed that will lead to a new generation of instruments capable of detecting low-mass planets and investigating solar-system-scale phenomena within protoplanetary disks in nearby regions of star formation.

OBJECTIVE 2: *To determine the frequency of occurrence of conditions suitable to the origin of life.*

The actual surface temperature of any particular planet will depend upon the abundances and chemical nature of its atmospheric constituents as well as its distance from the host star. Obtaining information on surface temperature and the chemical composition of an atmosphere requires direct imaging and spectroscopic analyses of each distant planet body. The technology required for such spectral studies is not yet available and may not be available when a statistically interesting number of extrasolar planets are first recognized. Models for their atmospheric composition will have to be constructed on the basis of comparative planetology (including the major planetary satellites) in our own solar system, together with what is known about the origin of the Earth's current and precursor atmospheres. Predictions made on the basis of outgassed and accreted atmospheric constituents must be compared with spectral data as soon as instrumentation permits. The goal is to understand just how often conditions suitable for life occur in the Milky Way galaxy.

Once terrestrial-mass planets have been detected, they must be analyzed spectroscopically to assess their atmospheric composition as well as their surface temperatures and pressures. This will provide an estimate of the frequency of occurrence of conditions similar to those that are presumed to have given rise to life on this planet. To appreciate the intrinsic difficulty of this task, it is necessary to remember that we have only been able to

accomplish a similar assay of Titan in the past few years and are still waiting for a probe mission to resolve speculations about a liquid organic ocean there. Titan presents a far bigger and brighter target than a distant Earthlike planet and one that can be observed without confusion from the solar luminosity. For these studies, therefore, it is important to continue the development of technologies for supersmooth mirror production, low-light-scattering telescopes, and large-orbital infrared, submillimeter, and optical telescopes that may eventually permit the direct imaging and gross atmospheric characterization of distant planets.

OBJECTIVE 3: *To search for presumptive evidence of life in other planetary systems.*

The probability that life, once started, will evolve to intelligence depends on many things, one of which may well be the fortunate location of a planetary system within the parent galaxy now or at some past epoch. If evolution toward intelligence everywhere requires billions of years, then changes in the astrophysical environment may play a central role in the process. Extinction events and evolution itself have been episodic on Earth (see Chapter 5). There is strong circumstantial evidence for an astrophysical connection in at least some of these episodes. Changes in the characteristics of the solar system have been most convincingly cited, but changes in our galactic location have also been suggested as causative agents.

In the foreseeable future, detection and spectroscopic study of extrasolar planets will be confined to the immediate galactic neighborhood. The peculiar velocities of our stellar neighbors will ensure that some of them have sampled far different galactic environments than Earth has in the past billion years. Given a sufficiently large sample of planets examined for signs of life and sufficiently accurate models for galactic dynamics, it might be possible to draw some conclusions regarding the probability of life arising and evolving as a function of galactic locale.

Any potentially suitable terrestrial-type planets must be studied in detail to search for signs of nonequilibrium chemical constituents, possibly signifying the action of some form of active biological system. Although the overabundance of molecular oxygen in the Earth's atmosphere and its coexistence with methane is an example drawn from Earth that correlates with life as we know it, life as we do not know it is likely to be no less surprising than the soil chemistry of Mars. The key to a distant atmosphere may lie in the coexistence of two other highly reactive components requiring a source function for which no natural planetological explanation can be found.

OBJECTIVE 4: *To search for evidence of extraterrestrial technology.*

Because the instrumentation for detecting evidence of extraterrestrial technology is far more mature than the instrumentation necessary for examining distant planets minutely, another technology (and, by inference, an-

other biology exhibiting intelligence) may be detected before any other evidence is found for extraterrestrial life. The examination of distant planets first requires the identification of such planets, but searches for other technologies can be made in the direction of plausible targets without a priori knowledge of the existence of a suitable planetary abode. Furthermore, searches can also be indiscriminate with respect to direction if the technology of another advanced civilization is sufficiently "loud." Thus, several different search strategies, based on different concepts of what constitute the most detectable features of a distant technology, may have to be employed in conducting an exhaustive search for signs of extraterrestrial technology. Such searches can attempt to detect purposeful communication signals, whether intended for Earth or for some other receiver. Because such signals are intentional, they can be expected to present a high signal-to-noise ratio for whatever communication scheme is utilized. In this case, it is possible to define what constitutes an exhaustive search. One must also use current terrestrial technology as a paradigm and formulate the sensitivity required to "see" the leakage radiation that is generated on Earth from across the galaxy. In the case of intentional beacons, it is not necessary to achieve this extreme sensitivity because intentional beacons could be much brighter. However, it is necessary to define this limit and use it as a standard against which to measure the significance of negative results.

Searches can also be conducted to detect the by-products of noncommunicative technologies of other civilizations. Intentional amplification is not expected to be imposed on these signals, and it is far more difficult to define what constitutes a definitive search for such evidence. Nevertheless, searches that can achieve some well-defined detection sensitivity should be pursued.

MEASUREMENT REQUIREMENTS

For the recommendations and scientific objectives outlined in the previous section to be accomplished, certain measurement accuracies must be achieved in a number of different observational technologies. It is appropriate for this report to compare the required accuracies to those likely to be achieved by various facilities, including mature missions nearing launch and those whose planning is well under way. In those areas where the available accuracies match or exceed the required ones, the research objectives of exobiologists can probably be accommodated by the appointment of specialists in this field as interdisciplinary scientists and by widespread distribution of announcements of opportunity. Facilities whose near-term available accuracies fall short of requirements will entail basic technological development so that subsequent generations of instrumentation will be able to provide the necessary capabilities for exobiological purposes.

Detecting Extrasolar Planets

An extensive literature exists on the techniques for carrying out searches for extrasolar planetary systems and their current or expected capabilities. Recent discussions may be found in *Space Science in the Twenty-First Century* (SSB, 1988b). With the exception of direct detection techniques, little has changed since these comprehensive reviews, and this report only briefly summarizes the measurement accuracies required to detect either Jupiter or the Earth in orbit about the Sun if these systems were located at a distance of 10 parsecs (30 light-years).

Extrasolar planets may be imaged directly or detected by one of three indirect techniques: astrometry, spectroscopy, and photometry.

Indirect Detection

1. Astrometric detection: Astrometry uses distant "fixed" stars as a reference frame against which to measure, over long periods of time, the relative position of a candidate star. A star and planet orbiting a common center of mass introduce a barely discernible reflex motion, or "wobble," into the stellar trajectory. The maximum amplitude of the reflex is 0.5 milliarc sec (500 microarc sec) for Jupiter and the Sun observed at a distance of 10 parsecs, and 0.3 microarc sec for the Earth and the Sun at the same distance. Atmospheric turbulence limits the obtainable ground-based measurement accuracy to something in excess of 100 to 300 microarc sec. Although nearby Jupiters can be detected from good ground-based sites, astrometric detection of even the closest Earthlike planet will require a space-based platform. Any instrumental system must possess extreme stability over very long time scales commensurate with planetary orbits, because it is the periodic nature of this reflex that ultimately distinguishes measurement from noise.

2. Spectroscopic detection: The same wobble in the star's motion induced by a star and planet orbiting about their common center of mass can be seen spectroscopically if the plane of the orbits is nearly parallel to the line of sight. In this case the change in relative velocity introduced as the stellar candidate moves toward or away from the observer can be seen as a periodic Doppler shift in the absorption line spectrum of the stellar photosphere. The effect of Jupiter on the Sun is to cause a maximum shift in velocity of 12 m/s, whereas the maximum effect induced by a terrestrial mass planet is 0.1 m/s. These small velocity shifts must be detected on top of photospheric turbulence and the peculiar velocities of the stars moving through space at tens of kilometers per second with respect to the observer. Except for accuracy limits imposed by the brightness of the star, this technique is independent of the distance to the star. Again, the measurements

demand extreme instrumental stability over long periods of time and a periodic signature associated with the velocity shift to distinguish signal from noise. Because the atmosphere does not seriously impede these spectroscopic studies, they can be conducted from the ground, and several facilities have already achieved instrumental accuracies sufficient to detect the effects of a Jupiter-mass planet. The recent announcement of seven stars that exhibit spectroscopic shifts $\gtrsim$10 m/s is extremely exciting. Measurements must be continued over the next decade to identify the underlying periodicity before definitive conclusions can be drawn. The limiting factor in this approach is the lack of detailed knowledge about any periodic or quasi-periodic processes in stellar photospheres that might induce Doppler shifts of this order internal to the star. Continued observations of the Sun's whole disk are required to determine the eventual sensitivity limit of this method.

3. Photometric detection: Astrometric and spectroscopic detection schemes have a long history, and both have recently benefited from a new generation of instrumentation. The next generation or two of astronomical instrumentation may enable a third detection scheme.

If the orbit of a planetary system is very well aligned with the observer's line of sight, then it is theoretically possible to detect the periodic decrease and slight change in color of the stellar luminosity produced when all or part of the stellar disk is occulted by a planet. This measurement requires extreme accuracy, far beyond current capabilities. Absolute photometry to a precision of 1 ppm in two different color bands is required to conclude reliably that the diminution of stellar luminosity is due to an occultation and not intrinsic fluctuations. The periodic nature of the effect is also a necessary characteristic. Since this method of detection was reviewed (SSB, 1988), ground-based measurements have achieved a photometric accuracy of 2×10^{-5}. Observations from Skylab indicate that Jupiter occulting the Sun would be relatively easy to detect from afar but that the Earth would be detectable only in quiet phases of solar activity. Because it is impossible to know in advance the inclination of a planetary system's orbital plane or when an occultation might occur, this technique is intrinsically a statistical one. Many stars must be monitored simultaneously and more or less continuously. Debatable, and rather optimistic, calculations suggest that monitoring 4000 stars with the requisite photometric accuracy will provide a detection rate of about one planet per month. Because the atmosphere severely degrades photometric precision, this detection scheme requires an instrument in Earth orbit. The double differential photometer required for the job is at least one generation of technology away, but this particular method may be worth pursuing because it is best suited to the detection of the small-orbit, short-period planets within any system. The real utility of this approach may eventually be to search for the inner planets of planetary systems already detected by other methods. In general, all the other meth-

ods work best for low-mass stars and high-mass planets. It is Jupiters that will be found (if anything) in the near future, not other Earths.

Direct Detection

To image a planet directly it is necessary to resolve its combined internal luminosity and reflected starlight from the overwhelming luminosity of the nearby star. For the Jupiter-Sun system at 10 parsecs this requires being able to achieve a brightness contrast ratio of 2×10^{-9} at visible wavelengths (or 10^{-4} at infrared wavelengths) just 0.5 arc sec away from the star. The Earth-Sun system at 10 parsecs would require a contrast ratio of 2×10^{-10} (or 10^{-6}) at a distance five times closer to the star (0.1 arc sec). No system in existence on Earth or planned for orbit comes close to achieving these accuracies. In the near future the only planets to be directly imaged will be massive, in large orbits about low-mass stars, or much closer than 10 parsecs.

Since the SSB reviewed the potential for direct imaging and recommended consideration of low-light-scattering requirements for future telescopes (*A Strategy for the Detection and Study of Extrasolar Planetary Materials: 1990–2000,* SSB, in press), there have been new studies yielding promising results. The combination of a coronagraph to reduce the diffraction of starlight by the telescope and a supersmooth mirror to reduce scattered light holds great promise for the future. One system currently under study is called the Circumstellar Imaging Telescope (CIT). This telescope should greatly reduce diffracted light in the wings of an image of a point source (Airy pattern) over the entire field of view of the instrument. Such an instrument would have to orbit the Earth to get above the detrimental effects of atmospheric viewing. A 2-m-diameter instrument in Earth orbit would allow the direct detection of a Jupiter-sized planet around a solar-type star out to a distance of approximately 10 parsecs. A larger instrument 10 m in diameter would be required to detect the Earth out to these distances, and the technology for such a large mirror has not been demonstrated.

In the CIT, diffraction is controlled by a Lyot coronagraph. Combining a Lyot coronagraph with apodizing occulting masks in the first focal plane can probably reduce the contribution from diffracted starlight by a factor of 1000. However, this factor of improvement in diffracted light can be utilized only if the scattering due to figure error in the primary mirror and to surface dust or scratches is at least 1000 times less than the diffraction of a conventional mirror.

Supersmooth mirrors have been manufactured for use in the fabrication of microelectronics. These mirrors (0.5-m-diameter spherical mirrors) have been characterized as approximately five times smoother than the Hubble

Space Telescope mirror. During the fabrication of supersmooth mirrors, figure errors decrease monotonically until the desired specification is reached and then polishing stops. The metrology used to measure the figure of the mirrors can go beyond the current specifications, and there appears to be no inherent reason why much smoother mirrors could not be fabricated. This promising technology should be pursued in coming years.

Studying Nebulae and Disks

The study of protoplanetary nebulae and young stellar disk systems also requires direct imaging techniques. Estimates of the required measurement accuracies for studying solar-system-scale objects at 10 parsecs or at 140 parsecs (Taurus molecular cloud star-forming region) follow. To resolve a linear dimension of 1 AU at 10 parsecs requires a resolution of 0.1 arc sec, whereas the diameter of our solar system (100 AU) can be resolved with a resolution of 10 arc sec. In the Taurus cloud, the corresponding resolutions become 0.007 arc sec and 0.7 arc sec, and resolving something even as large as a dusty protoplanetary nebula for a 1-solar-mass star in the Taurus cloud still requires a spatial resolution of 80 arc sec (1.33 arc min). To study dusty disks around young stars or protoplanetary nebulae in the process of collapse requires more than just spatial resolution; spectral resolution and good sensitivity are necessary. Resolving powers ($\lambda/\Delta\lambda$) as high as 10^5 may be needed to use far-infrared, submillimeter, and millimeter molecular lines as tracers of the kinematics and chemistry of the collapsing nebulae. To locate the inner cutoff (if any) of a dust disk around a young star and to characterize the particle size distribution and density as a function of radius require the ability to suppress the luminosity of the central star, as in the case of individual direct planet detection. Once again, coronagraphs can be used, but their physical size will ultimately determine how close to the star the measurements can be made. Ground-based interferometers at millimeter, submillimeter, and infrared wavelengths may prove to be the instruments of choice to study the radial dependence of the continuum emission from the dust. Long baselines, large collecting area elements, or many elements are required for sensitivity.

Spectroscopic Analyses of Planetary Atmospheres

To achieve the most ambitious objectives of remotely detecting, characterizing, and searching for evidence of life on an extrasolar planet, direct light from the planet must be examined without contamination from the light of the parent star. Only direct methods of planet detection are suitable for obtaining these observations. In the future, large systems employing coronagraphs, apodization, and supersmooth mirrors with diameters $\geq$10 m

may allow full characterization of the temperature, pressure, atmospheric composition, etc., of extrasolar planets. These large-aperture instruments may be monolithic but will most likely be composed of multiple phased elements. Therefore, additional technologies involved in stabilization of the point spread function of a multiple-element telescope will be needed.

An alternative to a very large-aperture telescope has recently been suggested for imaging a distant Earthlike planet and spectroscopically analyzing its atmosphere in search of oxygen and ozone: an optical aperture-synthesis interferometer. In particular, a 25-element array of 2.8-m anodized mirrors with surface accuracies comparable to the Hubble Space Telescope might be able to achieve sub-arc-second resolution sufficient to isolate planet and star. The stellar light can be satisfactorily suppressed by the combined effects of apodization and precise positioning of the star in a null of the interferometer. Very preliminary calculations suggest that 60 hours of integration time would be required for a 10-sigma detection of the 7600-Å oxygen A-band absorption feature for an Earthlike planet at the distance of Tau Ceti (~1 parsec). If the distance is increased to 10 parsecs, the required integration time increases to 300 hours. Whether such a scheme is feasible will depend ultimately on the accuracy with which the elements of the array can be maintained in relation to one another so that the star can be kept precisely at the interferometer null and the signal phase can be maintained. The positional requirements are extraordinary, far in excess of today's capabilities.

Unless they are fortuitously close, the direct imaging and spectroscopic analysis of Earthlike planets are not likely to occur within the time scale envisaged in this report. Continued development and research are required to ascertain whether very large smooth mirrors or extreme positional accuracy in space can actually be demonstrated by the next generation of technology. The search for primitive life may not yet be timely, but the development of technology to meet required measurement accuracies is. The problem of finding life beyond the solar system may become more tractable if there exist extraterrestrial technologies engaged in activities that can be detected remotely.

Searching for Extraterrestrial Technologies

Technologies That Generate Electromagnetic Signals

One very practical test of the idea that intelligent life exists beyond our solar system is based on the postulate that other technologies have transmitted (either deliberately or unintentionally) electromagnetic signals that can be received and recognized with extant technology here on Earth. In 1959, it was proposed that transmissions in the neighborhood of the spectral line

of neutral hydrogen (1420 MHz) might be a means by which extraterrestrial technologies communicate with each other over interstellar distances. More than two decades of scientific debate and review have expanded this idea into a plan to systematically search through the terrestrial microwave window for signals originating from an extraterrestrial source of intelligence. The plan calls for the use of existing radio telescopes, mature microwave technology, and very large special-purpose multichannel spectrum analyzers and signal-processing systems to carry out a promising set of exploratory search strategies. The entire sky is to be scanned with moderate sensitivity over the frequency range of 1 to 10 GHz. A set of about 800 nearby solar-type stars will be targeted for much more sensitive searches over the 1- to 3-GHz frequency range. The types of signals sought are those believed never produced by any natural process; they are compressed in frequency and perhaps in time as well. If implemented soon, this plan (which was recommended by the Astronomy Survey Committee in *Astronomy and Astrophysics for the 1980s,* Volume 1, National Research Council, 1982) should occupy most of the decade to be covered by this document.

The measurement accuracy appropriate for such a search strategy may be determined by establishing the sensitivity required to detect the artificial microwave signals generated by current terrestrial technology, if the planet Earth was assumed to be located across the Milky Way galaxy from us. Since we do not deliberately transmit signals intended for communication with another technology, the Earth model must consist of signals generated for our own purposes that leak into interstellar space. The weakest, but by far the most numerous, signals are the narrowband carriers for radio and television broadcasts; these are rated at 10^6 to 10^7 W of effective isotropic radiated power (EIRP). The single strongest, though very infrequent, signal transmitted is the Arecibo planetary radar at 10^{13} W EIRP. If these transmitters were located across the galaxy at a distance of 20 kiloparsecs (60,000 light-years), detection would require a sensitivity ranging from 10^{-37} to 10^{-30} W/m^2 for signals with EIRP ranging from 10^6 to 10^{13} W. For comparison, a typical molecular line survey made by radio astronomers achieves a sensitivity of 10^{-20} W/m^2. The planned NASA Sky Survey will achieve 10^{-23} W/m^2 and, at its most sensitive, the planned NASA Targeted Search will achieve 10^{-27} W/m^2. Successful detection by this planned search will require the existence of extraterrestrial transmitters that are more powerful (perhaps intentional) or closer than the other side of the Milky Way.

Although the planned microwave search will not conclude until nearly the end of the next decade, advanced planning for follow-on searches should be conducted concurrently. The planned microwave search may fail to detect any signals, either because the strategy is flawed or because the sensitivity and coverage of parameter space were inadequate. The microwave region of the spectrum is "preferred" for such signal detection be-

cause the natural astrophysical background radiation is least at those frequencies. The naturally quiet microwave window extends to at least 100 GHz, and signals from orbital transmitters may occupy the upper end of the window. The planned microwave search is restricted to the lower portion of the window by the increased atmospheric noise inherent to any terrestrial ground-based search. Future searches will require access to space to extend the search to higher frequencies and to escape the increasing interference generated by terrestrial communication technology. Conclusions concerning the best possible signal-to-natural-noise ratio as a function of frequency (if space-based transmitters and receivers are assumed) depend upon scaling laws for the construction of orbital structures. Under certain scaling laws, the infrared appears to provide the best signal-to-noise ratio; under others, the microwave region is still preferred. Experience with on-orbit construction in the coming decades will allow an empirical determination of how the size of an antenna scales with wavelength. Therefore, it is essential to consider and review other plausible strategies for the detection of electromagnetic signals from technologies that generate them and to support development of those that are worthwhile, should they be required.

Technologies That Do Not Generate Electromagnetic Signals

Even a highly technological civilization might not deliberately generate signals that are detectable over interstellar distances. The question is then whether the technology of such a civilization could be detected in some other way. It is impossible to extrapolate the likely progress of technology, here or elsewhere, with any degree of certainty. Although speculative, however, it is appropriate to consider those technological activities in which we now engage and ask how they might appear from afar if they were increased in scale and intensity as some scientists and engineers have proposed.

Energy production or transformation will probably be an important concern for any advanced technology. Collection of stellar radiation on a planetary-system scale, large-scale stellar disposal of fissionable waste, and tritium leakage from orbital fusion plants might produce anomalous radiation in the infrared, in the optical lines associated with rare earth elements, and at microwave frequencies, respectively. Thus, there could be observable signatures of energy production by advanced civilizations, but it is not possible to make any quantitative predictions. However, in the event of unexpected or unusual observational results during the pursuit of more traditional research, such explanations should be kept in mind if known astrophysical causes cannot be found easily. No separate or discrete efforts seem to be indicated in this line of research. It is important to lend support to the development and deployment of new and more capable infrared in-

strumentation for the study of protoplanetary nebulae and dusty disks around young stars. Continuation of the classical study of stellar spectra and improved instrumentation to make the process more efficient are important in their own right. Detection of another technology might be a serendipitous bonus.

Interstellar travel and colonization, if undertaken by a distant technology, might well have extraordinary observational consequences. However, because this takes us beyond the realm of extrapolation of our current technology, it is not appropriate for this report.

Available Measurement Accuracies

Now that the measurement accuracies required have been derived to detect extrasolar planets, spectroscopically scan their atmospheres, and detect evidence of extraterrestrial electromagnetic technologies, it is necessary to compare them with what is likely to be available in the near future.

Tables 6.1 through 6.4 provide a summary of existing instrumental capabilities and possible future prospects for the four methods of extrasolar planetary detection discussed above. Table 6.5 is a summary of the observational capabilities for NASA's proposed Microwave Observing Project.

Innovations, breakthroughs, and perhaps completely new technologies are required to directly image terrestrial planets, perform chemical assays

TABLE 6.1 Instruments for the Detection of Extrasolar Planets: Astrometric Methods

Telescope/Spacecraft	Launch	Instrument	Resolution (arc sec)
Allegheny Observatory	Now	MAP	10^{-3}
Lick Observatory	Now	Image detector	10^{-3}
Hubble Space Telescope	1990	WFC	10^{-3}
		FGS	10^{-3}
Dedicated new astrometric telescope on Mauna Kea	?	MAP	10^{-4}
Imaging astrometric free flyer	?	MAP	10^{-4}
ATF on Space Station	1995	MAP	10^{-5}
Free-flying astrometric interferometer	?	Moving grating	10^{-6}

NOTE: ATF = astrometric telescope facility; FGS = fine guidance sensor; MAP = multichannel astrometric photometer; WFC = wide-field camera.

TABLE 6.2 Spectroscopic Detection

Telescope/Spacecraft	Launch	Instrument	ΔV (m/s)
Ground-based facilities (6) spectrometer	Now	Radial velocity	10

TABLE 6.3 Photometric Detection

Telescope/Spacecraft	Launch	Instrument	$\Delta\lambda/\lambda$
Space Station Block II	1999	Double differential spectrometer	10^{-5}

TABLE 6.4 Direct Detection

Telescope/Spacecraft	Launch	Instrument	Resolution (arc sec)	Contrast
Ground-based speckle and coronagraphs	Now (Keck in 1991)	IR CCDs	1-2	5×10^{-2}
			0.5	10^{-3}
Hubble Space Telescope	1989	FOS and coronagraph	1	2×10^{-7}
Hubble Space Telescope, 2nd generation	1994	NICMOS or HIMS	0.2	10^{-5}
			0.1	10^{-5}
ISO	1992	ISOCAM	6	10^{-3}
SIRTF	1995	MIPS	6	10^{-3}
CIT	1995	Coronagraph	1	10^{-9}
FIRST	?		1	10^{-3}
LDR	?		1	10^{-3}
Dedicated IR interferometer	?		0.5	10^{-4}
Optical interferometer	?		0.3	10^{-10}

NOTE: CCD = charge coupled device; CIT = Circumstellar Imaging Telescope; FIRST = Far-Infrared Space Telescope; FOS = faint-object spectrograph; HIMS = Hubble imaging Michelson spectrometer; IR = infrared; ISO = Infrared Space Observatory; ISOCAM = Infrared Space Observatory camera; LDR = large deployable reflector; MIPS = multiband imaging photometer; NICMOS = near-infrared camera and multiobject spectrometer; SIRTF = Space Infrared Telescope Facility.

TABLE 6.5 Search for Technological Civilizations That Generate Electromagnetic Signals

Dual Mode Search Strategy for NASA's Microwave Observing Project
Targeted Search
800 nearby solar-type stars
Up to 1000 s of observation per star at each frequency band
1- to 3-GHz frequency coverage
Dual circular polarization
High resolution and sensitivity
Sensitivity to a wide variety of signals pulsed and drifting continuous wave (CW)
On-line RFI subsystem
120 million channels (1-, 2-, 4-, 8-, and 16-Hz and 74-kHz resolution bandwidths)
Sky Survey
All-sky coverage
0.3 to 3 s of observation per beam at each frequency band
1- to 110-GHz frequency coverage
Dual circular polarization
Moderate resolution and sensitivity
Primary sensitivity to CW signals
RFI data base
15 million channels (30-Hz and 74-kHz resolution bandwidths)

thereon, search for leakage radiation throughout the galaxy, and move the search for extraterrestrial technologies to higher frequencies or to other search concepts.

Advances will be needed in technologies required for interference protection of a large dedicated SETI facility in high Earth orbit or on the lunar farside; for large-scale optical, infrared, and submillimeter arrays in Earth orbit or on the lunar farside for direct imaging and spectroscopic examination of extrasolar planets and protoplanetary nebulae; and for advanced data-processing techniques.

7

Major Research Recommendations

The recommendations in this chapter fall into two general categories: those that require observations and experiments to be conducted on either planetary missions or facilities in Earth orbit and those that include observations, experiments, and theoretical modeling studies that can be carried out in ground-based facilities. In view of the generally large differences in cost and complexity between these two categories, the committee assigns priorities within the two groups separately. Within each group, lists have been priority ordered on the basis of a combination of near-term feasibility and scientific importance. In making recommendations involving space flight, it should be recognized that the principal impetus for these missions is most likely to stem from the astrophysical and planetary scientific communities and that the resources involved in performing exobiological studies thereon will typically be very much less than overall mission expenses. It should also be noted that obtaining the full potential from such missions will require the participation of scientists with interests in planetary biology and chemical evolution from the inception of planning.

RECOMMENDATIONS REQUIRING FLIGHT OPPORTUNITIES

Mars

The highest priority in the category requiring flight missions is accorded to studies of Mars. It is hard to imagine more exciting and fundamental questions than those concerning the early surficial environment and the possibility of chemical or even biological evolution on the early surface of our neighboring planet. Furthermore, Mars is the only other object in the solar system on which an earlier origin of life could have left a well-

preserved, exposed record. Sedimentary rocks on Mars may contain a record of the interval in chemical evolution that is nowhere preserved on the Earth and may thus contribute to understanding the processes that led to the origin and early evolution of organisms on this planet. Thus, investigations of Mars can contribute to the elucidation of objectives discussed previously in connection with early planetary environments and the origin of life—both on the Earth and, possibly, on Mars—as well as with the course of biological evolution on this planet. (More complete discussions of these issues can be found in Chapters 3 [pp. 71–77] and 5 [pp. 102–103]). The committee therefore recommends studies to

- **conduct chemical, isotopic, mineralogical, sedimentological, and paleontological studies of Martian surface materials at sites where there is evidence of hydrologic activity in any early clement epoch, through in situ determinations and through analysis of returned samples; of primary interest are sites in the channel networks and outflow plains; highest priority is assigned to sites where there is evidence suggestive of water-lain sediments on the floors of canyons as in the Valles Marineris system, particularly Hebes and Candor chasmata; and**
- **reconstruct the history of liquid water and its interactions with surface materials on Mars through photogeologic studies, space-based spectral reflectivity measurements, in situ measurements, and analysis of returned samples.**

Comets and Asteroids

Critical information about the chemical nature, and early processing, of materials containing the biogenic elements (i.e., the evolution of organic complexity in the solar nebula) can be obtained from the study of these relatively unmetamorphosed materials of the solar system. These issues are more fully discussed in Chapters 2 (pp. 46–48, 51–53, and 55) and 3 (pp. 61–62). Such studies can lead to an understanding of the role of these bodies in supplying the primitive Earth with the organic constituents and volatiles necessary for the origin of life on the planet. Furthermore, these bodies are also of interest as projectiles that may have had significant effects on the course of biological evolution by impacting the Earth. The committee therefore recommends that

- **measurements be made, by remote spectroscopic observations, and in situ, of the elemental and isotopic composition of cometary comae and nuclei, and of the principal asteroid types, including determination of the molecular composition of components containing the biogenic elements hydrogen, carbon, nitrogen, oxygen, phosphorus, and sulfur in comets and primitive asteroids; such measurements should be made at**

various surface locations and depths to determine the degree of homogeneity; and

- **a cometary sample be obtained for detailed laboratory analysis of atmospheric, surface, and subsurface materials.**

Titan and the Giant Outer Planets

The outer planets, in contrast to the inner, represent bodies with atmospheres dominated by hydrogen and containing organic constituents. Study of these objects can yield considerable insight about the processes involved in the formation of organic compounds under natural conditions in a hydrogen-rich environment. Much interesting chemistry must also be taking place in the strongly reducing atmosphere of Titan. Thus, investigations of these objects can be expected to shed much light on one model for the formation of life on the Earth, in which a reducing atmosphere has been invoked. The committee therefore recommends studies to

- **identify the compositions, and measure the abundances and distributions, of gaseous organic compounds and organic haze particles in Titan's atmosphere, using atmospheric entry probes and remote astronomical observations** (see Chapter 3, pp. 59–61); and
- **elucidate the distribution, with altitude, of organic matter, carbon monoxide, and phosphine in the atmospheres of Jupiter and Saturn by using atmospheric entry probe measurements and astronomical observations** (Chapter 3, pp. 58–59).

The Interstellar Medium and Cosmic Dust Particles

The earliest stages of chemical processing involving the biogenic elements are taking place in molecular clouds and protosolar nebulae. Studies of these objects can therefore answer fundamental questions about the early history of organic chemical evolution. For investigation of the interstellar and protostellar regions, significant advances in the understanding of early organic chemical evolution can be realized by opening up those portions of the infrared- through millimeter-wavelength spectrum for which the atmosphere is opaque. Additional opportunities to increase understanding of processes and events in the evolution of volatiles and organic materials in the early solar system can be attained by the study of extraterrestrial dust particles. The two recommendations below follow from discussion in Chapter 2 (pp. 34–41 and 25–34). For effective probing of these scientific issues, the committee

- **strongly supports the development of high spectral resolution,**

Earth-orbital facilities for astronomical observations at infrared, submillimeter, and millimeter wavelengths; and

- **recommends Earth-orbital collection of interplanetary (and potentially interstellar) dust particles—including, ultimately, nondestructive methods of collection—to allow their detailed chemical and isotopic analysis.**

RECOMMENDATIONS REQUIRING GROUND-BASED STUDIES

Chemical Evolution and the Origin of Life

Scientific developments over the past decade that bear on the processes leading to the origin of life have resulted in an expansion in emphasis from prebiotic chemistry into biochemical evolution as well. One consequence of this expansion is that work of high interest to the exobiology community, and supported by NASA, has increasingly come to overlap studies supported by other federal agencies such as NIH and NSF. NASA's continuing support is critical, however, because only it provides the programmatic integration that promotes the necessary cross-fertilization of the various disciplines relevant to exobiology. As in the past, NASA programs in this field should strive to avoid duplicating the efforts of other agencies and should complement the work of these agencies by focusing on issues that directly concern interactions between the physical and chemical environments that led to the development and evolution of organisms on this planet. Accordingly, the committee recommends:

- **the reexamination of biological monomer synthesis under primitive Earthlike environments, as revealed in current models of the early Earth, and the synthesis and study of simple model systems for fundamental biological processes such as polynucleotide replication, sequestration of biomolecules, coenzyme functions, and elements of the translation system in protein syntheses** (this recommendation is based on considerations discussed in Chapter 4 [pp. 80–90]);
- **the development of improved data on the biological and physical development of the Earth by modeling the geochemistry of the prebiotic and earliest biotic oceans to obtain their composition and their physical and chemical responses to large impacts, and by careful sedimentological, geochemical, and paleontological analysis of ancient sedimentary basins; local environments favorable for the origin of life should be identified and characterized geophysically and geochemically: geological research should be aimed not only at the elucidation of environmental evolution, but also at understanding the cosmic influences on terrestrial environments and evolution** (see Chapters 3 [pp. 63–71] and 5 [pp. 93–102] for discussion of these points);

- **studies designed to recognize extraterrestrial signatures in sedimentary successions and research to evaluate temporal patterns in the composition of the biota (as recorded in the fossil record) in light of recognizable extraterrestrial signals** (see Chapter 5 [pp. 100–102]);
- **the continued search on Earth for igneous and sedimentary rocks formed prior to 3.8 billion years ago** (the background for this is discussed in Chapter 3 [pp. 65–69]); **and**
- **the development of robust phylogenies relating living organisms, through the comparison of sequences in informational macromolecules, especially small subunit ribosomal RNAs, and the elucidation of the biochemical and ultrastructural characters of microorganisms in order to relate patterns of phenotypic diversity to phylogeny** (these points are discussed in Chapter 5 [pp. 93–98]).

Mars-Related Studies

Ground-based studies, discussed in Chapter 3 (pp. 71–77), are necessary to understand present environmental conditions on Mars, as well as the history of the evolution of this environment in order to plan effective exploratory investigations related to exobiology. The committee therefore recommends that

- **laboratory and theoretical model studies be carried out of photochemical and weathering processes on Mars that will determine the nature of inorganic carbon, nitrogen, sulfur, and iron-bearing phases in Martian surface soils; will indicate the geochemical cycles of these elements during an earlier aqueous epoch; and will characterize the nature of the oxidants revealed by the Viking experiments; and**
- **scenarios be developed for chemical evolution and the origin of life on Mars, based on our knowledge of these processes on Earth, but bounded by existing data and theory on the accretionary, tectonic, geologic, and climatic history of Mars.**

Studies Related to Comets and Asteroids

These bodies of the solar system are of interest to the field of exobiology from many points of view: as projectiles impacting the planets, as possible sources for the biogenic elements and volatiles on the terrestrial planets, and as reservoirs of information about the early history of the solar system. In relation to these issues, the committee recommends

- **maintenance of a vigorous program of research on the chemical, isotopic, mineralogical, and petrographic properties of meteorites, and laboratory studies of the molecular and isotopic compositions and yields**

of organic molecules produced in realistic simulations of those astrophysical environments within which presolar constituents of carbonaceous meteorites may have been produced (see Chapter 2 [pp. 48–51]); **and**

- **theoretical studies on the physics of comet formation to determine the maximum size of comets accreted in the solar nebula, as well as thermocalculations of the composition of atmospheres produced by large impacts of cometary and various asteroidal-type bodies** (see Chapters 2 [pp. 51–53] and 3 [pp. 61–62] for a discussion of this topic).

Studies Related to Titan and the Giant Outer Planets

Theoretical modeling and laboratory studies are required to elucidate the organic chemistry in the atmospheres of Titan and the giant planets, as well as to effectively interpret relevant data obtained from missions to these objects, which are discussed in Chapter 3 [pp. 58–61]. The committee therefore recommends that

- **simulations be carried out of organic synthesis resulting from the deposition of electrons, photons, and cosmic rays into Titan's atmosphere and that similar experiments, as well as computer simulations, be conducted that will yield predictions of the molecular compositions and abundances of organic matter produced by processes operating at various levels in the atmospheres of Jupiter and Saturn.**

Studies Related to the Interstellar Medium and Dust

Data from laboratory investigations and from theoretical modeling are necessary to prepare for, understand, and extend the results obtained from space-borne experiments aimed at studying the interstellar medium and dust particles of interstellar and interplanetary origin. For these purposes, the background of which is given in Chapter 2 (pp. 25–45 and pp. 53–54), the committee recommends

- **study of the spectra of, and chemical processes involving, potential gas and grain constituents of molecular clouds that are the sites of star and planetary formation, as well as the study of gas and grain reactions under conditions consistent with realistic models of the solar nebula, including a variety of nonequilibrium processes, and of the growth and destruction of grain aggregates;**
- **utilization of ground-based telescopic facilities to probe the chemistry and physics of star-forming regions in detail, and development of the instrumentation necessary to maximize the scientific return from**

space-based, laboratory, and telescopic measurements, including broad-bandwidth, high-resolution spectrometers and microanalytical techniques;

- **maintaining a vigorous program of research on the chemical and isotopic properties of dust particles of extraterrestrial origins; and**
- **theoretical modeling of chemical and physical processes, including grain growth, in the solar nebula and in interstellar, circumstellar, and protostellar environments.**

Studies Related to the Search for Life Outside the Solar System

Two parallel avenues of research should be pursued in attempts to detect life beyond the solar system: searches for evidence of biological modification of an extrasolar planet and searches for evidence of extraterrestrial technology. These separate approaches can conceivably influence each other. For example, if a nearby solar-type star is found to have a planetary system, it would become a prime target for a SETI-type search; similarly, if an "SETI signal" were detected from the direction of some nearby star, intensive efforts would undoubtedly be made to image and study the host planet. Because both lines of investigation can proceed simultaneously, the overall priorities listed below are those suggested naturally by the existing maturity of the requisite instrumentation. For these studies, the committee recommends

- **continued support for ground-based and Earth-orbital searches for extrasolar planets** (for discussion, see Chapter 6 [pp. 106–108, 109–112, and 113–117]);
- **commencement of a systematic ground-based search through the low end of the microwave window for evidence of signals from an extraterrestrial technology** (see Chapter 6 [pp. 111–112 and 117–122]); **and**
- **studies leading to the development of future technologies for these investigations, including large-scale optical, infrared, and submillimeter arrays or monoliths in orbit or on lunar farside for imaging extrasolar planets and protoplanetary nebulae; a dedicated SETI facility with RFI protection in high Earth orbit or lunar farside; advanced data-processing techniques; and substantive original or unconventional approaches to the detection of other technological civilizations** (this topic is discussed in Chapter 6 [pp. 117–122]).

8

Space Science Program and Policy Issues

As is apparent from the preceding chapters, research in chemical evolution and planetary biology extends over many "classical" scientific disciplines and brings together investigators from seemingly disparate areas. Over the last two decades, this field has developed to the point at which evolutionary themes on cosmological, chemical, and biological levels have become foundations from which studies are undertaken. With these common evolutionary themes and the exposition of continuous cause and effect between evolving biological and planetary systems, communication across scientific disciplines has become at least as important as within the disciplines themselves. Maintenance of this broad "mix" of biological and physical sciences, and of ground- and space-based investigations, is unique to the space sciences and critical to the effective conduct of a vigorous national program in chemical evolution and planetary biology.

The requirement for substantial interdisciplinary communication must be addressed if this program is to be fully successful. The following discussion is therefore aimed at strengthening and invigorating activities in this field.

ACCESS TO MISSIONS

The current efforts of NASA in chemical evolution and planetary biology are administered almost entirely by the Exobiology Program Office within the Life Sciences Division of the agency. On the other hand, planning for, and implementation of, space missions not directly concerned with space medicine or space biology are conducted by other divisions of NASA. In turn, these missions depend largely on advice from scientists with interests different from those discussed in this document. Nevertheless, many

data of direct relevance to planetary biology and chemical evolution have been derived from observations and measurements made for other scientific purposes. Although consideration has often been given to exobiology objectives in the developmental mission plans, much stronger interaction is needed between mission planners and the exobiology science community. To enhance the utility of future missions for those areas of inquiry that are the subject of this report, the advice of qualified scientists should be utilized in the planning and implementation of these missions.

One aspect of this issue is that investigators interested in chemical evolution and planetary biology are often precluded from making serious proposals for space-borne experiments because specific hardware or even concepts for flight instrumentation are not available for evaluation at the time of payload selection. To a large extent, this situation does not extend to other branches of NASA, which have historically devoted significant resources to the development of concepts for flight instruments as part of their ongoing programs. The committee therefore urges NASA to encourage the timely development of instrumentation for potential use in space experiments involving chemical evolution and planetary biology, well in advance of payload selection, by setting aside specific funds for this purpose.

MEASURES TO ENHANCE RESEARCH IN CHEMICAL EVOLUTION AND PLANETARY BIOLOGY

Because of the essential role of space technology in many aspects of research in chemical evolution and planetary biology, almost all of the support for this field, and for integration of its various elements, is now borne by a single federal agency, NASA, through its grants and in-house activities. Nevertheless, other federal agencies, notably the NSF and NIH, support research that may be directly related to the overall goals of this program. *NASA should explore mechanisms for closer interaction with its sister agencies in order to maximize the national efforts in this area, especially in areas that might be jointly funded.* Such interactions can serve to inform a much wider circle of scientists than might otherwise be reached of the goals, objectives, and opportunities of the NASA programs in chemical evolution and planetary biology and, at the same time, could bring new ideas and fresh approaches into the field.

In this regard, the committee is conscious of the fact that potentially interested scientists are often unaware of NASA's goals in this area. Furthermore, many are poorly informed about the procedures used by NASA in its grants program. Under these circumstances, valuable scientific resources are being inadequately tapped by the agency and are either diverted to other agencies or lost altogether. NASA should devise ways to reach more broadly into the scientific community by delineating and publicizing its goals and

objectives and also by establishing more clearly the procedures through which entry can be made into the program.

It is also important for NASA to educate the scientific community about the many areas of evolutionary biology in which data obtained from space missions have enhanced understanding of the course of evolution. *NASA should make a greater effort to bring to the attention of the scientific community the potential benefits to be derived from the use of space technology.* For example, as discussed earlier, clues to the early terrestrial environment almost certainly exist on Mars, the Moon, and elsewhere in the solar system, and a more complete understanding of this environment may only be obtainable by probing bodies.

Because of the interdisciplinary nature of this field, there is an obvious need for frequent and sustained cross communication among the various disciplines that contribute to the overall goals of the program. The committee acknowledges that interactions of this kind have taken place, but this activity needs to be intensified. To implement this need, NASA should establish procedures that will encourage more effective communication among molecular/evolutionary/biospheric biologists, paleontologists, astronomers, geologists, and planetary modelers both from within NASA centers and from the academic community. Opportunities for such interactions can be facilitated by NASA sponsorship of workshops, symposia, and innovative interdisciplinary research projects.

Also, because the subject matter of this field cuts across both the physical and the biological sciences, specific training in this area is not normally available to students as they prepare for their scientific careers, and young people entering the pool of scientific talent are less apt to seek careers in chemical evolution and planetary biology. To surmount this deficiency, NASA should develop a program of specific postdoctoral fellowships in the field by which candidates would be able to pursue advanced studies either at NASA in-house laboratories or with university specialists.

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Glossary

Å: Angstrom; unit of length.
achondrite: Differentiated meteorite.
anticodon: Triplet of bases in transfer RNA complementary to the codon.
archaebacteria: Organisms constituting one of the three biological kingdoms.
Archean: Period of Earth's history from 3.8 to 2.4 billion years ago.
arc sec: Arc second; unit of angular measurement in astronomy.
ATF: Astrometric telescope facility.
AU: Astronomical unit; mean distance between the Earth and the Sun.

biogenic elements: Elements making up the bulk of living organisms.

CAI: Calcium-aluminum inclusion, found in meteorites.
carbonaceous chondrite: Meteorite with granules containing carbon-rich matter.
CCD: Charge coupled device.
CIT: Circumstellar Imaging Telescope.
cm: Centimeter.
codon: Triplet code of bases in DNA specifying an amino acid in protein synthesis.
COMPLEX: Committee on Planetary and Lunar Exploration.
CRAF: Comet Rendezvous Asteroid Flyby mission.
Cretaceous: Period of Earth's history from 145 to 65 million years ago.

D/H: Deuterium-to-hydrogen ratio.
DNA: Deoxyribonucleic acid.
DOE: Department of Energy.

ECHO: *Evolution of Complex and Higher Organisms;* report.
EIRP: Effective isotropic radiated power.
ESA: European Space Agency.
eubacteria: All other bacteria besides the archaebacteria.
eukaryote: Cells with true nucleus and other internal organelles.

FGS: Fine guidance sensor.
FIRST: Far-Infrared Space Telescope.
Fischer-Tropsch reaction: Process in which carbon monoxide and hydrogen mixtures are converted into hydrocarbons and related compounds.
FOS: Faint object spectrograph.

genome: The complete set of genes in an organism.
GHz: Gigahertz; unit of frequency.

HD/H_2: Ratio of deuterated hydrogen to hydrogen.
heterocyclic organic polymers: Compounds consisting of monomeric units of organic ring molecules in which not all atoms in the rings are alike.
heterotroph: Organism requiring organic compounds as food source.
HIMS: Hubble imaging Michelson spectrometer.

IR: Infrared region of electromagnetic spectrum.
IRAS: Infrared Astronomical Satellite.
ISO: Infrared Space Observatory.
ISOCAM: Infrared Space Observatory camera.

J: Joule; unit of heat energy.

K: Kelvin; unit of temperature.
KAO: Kuiper Airborne Observatory.

L183: Interstellar cloud.
LDR: Large deployable reflector.

m: Meter.
MAP: Multichannel astrometic photometer.
MHz: Megahertz; unit of frequency.
MIPS: Multiband imaging photometer for SIRTF.

mRNA: Messenger RNA; directs the synthesis of proteins.
NAD: Nicotinamide adenine dinucleotide; coenzyme involved in redox reactions.
NASA: National Aeronautics and Space Administration.

NICMOS: Near-infrared camera and multiobject spectrometer.
NIH: National Institutes of Health.
NMR: Nuclear magnetic resonance.
NRAO: National Radio Astronomy Observatory.
NRC: National Research Council.
NSF: National Science Foundation.
nucleoside: Precursor of nucleic acids; consists of an organic base and a sugar.
nucleosynthesis: Production of elements heavier than hydrogen.

oligonucleotide: Short chain of nucleic acid monomers.
oligopeptide: Short chain of amino acids.

PAH: Polyaromatic hydrocarbon.
Paleozoic: Period in Earth's history from 670 to 245 million years ago.
Permian: Period of Earth's history from 285 to 245 million years ago.
Phanerozoic: Period of Earth's history from 670 million years ago to present.
phenotype: Observable physiological behavior of an organism.
phosphomonoesterase: Hydrolytic enzyme; releases inorganic phosphate.
phototroph: Organism deriving its energy from light.
phylogeny: Ordering of biological species based on their evolutionary relationships.
planetesimal: Solar-system body; of the order of a kilometer in size.
planetoid: Solar-system body; tens to hundreds of kilometers in size.
prebiotic: Before the appearance of life on Earth.
Precambrian: Period of Earth's history from its formation to 600 million years ago.
prokaryote: Organism lacking a true nucleus.
Proterozoic: Period of Earth's history from 2.5 billion to 600 million years ago.
pyrolysis: Destruction of organic compounds by combustion.

regolith: Surface debris on solar-system objects produced by impacting bodies.
RFI: Radio frequency interferences.
ribonucleotide: Monomeric unit of RNA.
ribooligonucleotide: Short chain of ribonucleotides.
ribosome: Cellular particle; site of protein synthesis.
RNA: Ribonucleic acid.
RNA polymerase: Enzyme that polymerizes ribonucleotides.
RNase P: tRNA-processing enzyme containing a catalytic RNA subunit.
rRNA: Ribosomal RNA; involved in protein synthesis.

S: Svedberg unit; sedimentation constant used in ultracentrifugation.
SAO: Smithsonian Astrophysical Observatory.
SETI: Search for extraterrestrial intelligence.
SIRTF: Space Infrared Telescope Facility.
SNC: Shergottite, nakhlite, and chassignite meteorites; possibly from Mars.
SSB: Space Science Board/Space Studies Board.

T4 RNA ligase: Enzyme causing ribonucleic acid fragments to join together.
template: Molecule that is copied to form its complement in nucleic acid synthesis.
thiol ester: Sulfur-containing ester.
TMC-1: Interstellar cloud.
translation: Process by which DNA code specifies sequencing of amino acids.
tRNA: Transfer RNA; combines with specific amino acid in protein synthesis.

UV: Ultraviolet region of electromagnetic spectrum.

Van der Waals force: Weak attractive force between nonpolar molecules.
Viking: U.S. mission to Mars in 1975.

W: Watt; unit of power.
WFC: Wide-field camera.

Appendix

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