density-separation jigs a form of gravity separation of materials with different densities that uses a pulsating fluid

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Astrobiology

Astrobiology is a new interdisciplinary science that studies the origin, evolution, distribution, and destiny of life in the cosmos. Other terms that have been used to describe the search for life beyond Earth include exobiology, exopaleontology, and bioastronomy. Astrobiology is a broadly based, interdisciplinary science that embraces the fields of biology and microbiology, microbial ecology, molecular biology and biochemistry, geology and paleontology, space and gravitational biology, planetology, and astronomy, among others.

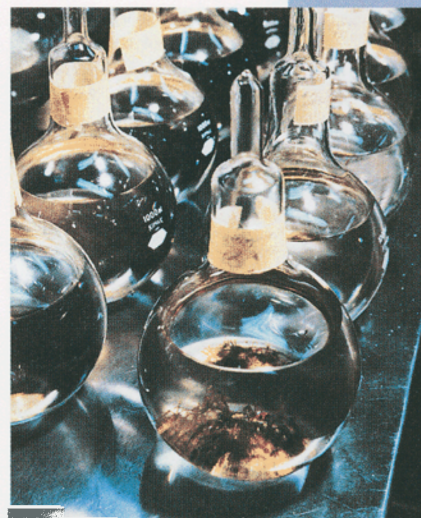
The development of astrobiology as a discipline began in the early 1990s with the recognition of a growing synergy between various sciences in seeking answers to the question of extraterrestrial life. The National Aeronautics and Space Administration (NASA) promoted the development of astrobiology by funding a research institute (the NASA Astrobiology Institute, or NAI), which consists of interdisciplinary teams of scientists from fifteen separate institutions in the United States, including both government laboratories and universities. Important scientific discoveries have changed the way scientists think about the origin, evolution, and persistence of life on Earth. These discoveries have helped fuel the growth of astrobiology by defining the broad conceptual framework and scope of the field and by opening up new possibilities for the existence of extraterrestrial life.

Earth's Microbial Biosphere

biosphere the interaction of living organisms on a global scale

Since the late 1980s, advances in genetics and molecular biology have radically altered scientists' view of the **biosphere** and the contribution of microbial life to planetary biodiversity. The opportunity to compare gene sequences from a wide variety of living organisms and environments has shown that living organisms cluster into one of three biological domains: the Archaea, Bacteria, or Eukarya. Each of these domains is made up of dozens of biological kingdoms, the vast majority of which are microbial. Species inferred to be the most primitive forms so far discovered are all found at high temperatures (greater than 80°C [176°F]) where they use simple forms of chemical energy. However, knowledge of Earth's biodiversity is still very much a work in progress. While biologists have sampled a wide range of environments, it is estimated that only a small fraction, perhaps 1 to 2 percent of the total biodiversity present, has so far been captured. Still, the three-domain structure has remained stable. New organisms are being discovered each year, adding diversity to each domain, but many discoveries still lie ahead.

These advances in biology have led to a growing awareness that Earth is overwhelmingly dominated by microscopic life and that these simple forms have dominated nearly the entire history of the biosphere. Indeed, advances in paleontology have now pushed back the record of microbial life to within half a billion years of the time scientists believe Earth first became inhabitable. This suggests that once the conditions necessary for life's origin were in place, it arose very quickly. Exactly how quickly is not yet known, but in geologic terms, it was a much shorter period than previously thought. This view significantly improves the possibility that life may have originated on other planets such as Mars, where liquid water may have been present at the surface for only a few hundred million years, early in the planet's history.



NASA's Controlled Ecology Life Support System studies self-contained systems for applications related to future space colony environments. These sealed flasks contain shrimp, algae, and other microorganisms capable of generating their own water, oxygen, and food.

***Oxygen currently makes up 21 percent of Earth's atmosphere.**

The Evolution of Complex Life

Studies of the fossil record have revealed that complex, multicellular forms of life (plants and animals) did not appear on Earth until about 600 million years ago, which is recent in geological history. Animals are multicellular consumers that require oxygen for their metabolism. Scientists believe that their late addition to the biosphere was triggered by the buildup of oxygen in the oceans and atmosphere to a threshold of about 10 percent of the present atmospheric level.* It is clear that the high level of oxygen found in the atmosphere today could have been generated only through photosynthesis, a biological process that captures sunlight and uses the energy to convert carbon dioxide and water to organic matter and oxygen. Clearly, oxygen-evolving photosynthesis has had a profound effect on the biosphere. If oxygen was required for the appearance of complex animal life, then a detailed understanding of photosynthetic processes and their evolution is crucial to create a proper context for evaluating the cosmological potential for life to evolve to the level of sentient beings and advanced technologies elsewhere in the cosmos. This research also provides a context for the SETI program (Search for Extraterrestrial Intelligence), which is currently exploring the heavens for advanced civilizations elsewhere in the galaxy by monitoring radio waves.

Basic Requirements for Life

The most basic requirement of living systems is liquid water, the universal medium that organisms use to carry out the chemical reactions of metabolism. Water is a unique dipolar compound (positively charged on one side and negatively charged on the other) with special solvent properties that allow it to act as a universal medium of transport and exchange in chemical reactions. In addition, the physical properties of water allow it to remain liquid over a very broad range of temperatures, thus enhancing its availability to living systems. In exploring for life elsewhere in the cosmos, the recognition of the importance of liquid water as a requirement for life is reflected in NASA's basic exploration strategy, which seeks to "follow the water."

But to exist, living systems also require sources of nutrients and energy. The common biogenic elements (carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur), which comprise the basic building blocks of life, appear to be widely distributed in the universe. These elements are forged in the prising given that, per unit area of Earth's surface, energy from the Sun is several hundred times more abundant than the thermal and chemical energy sources derived from *within* Earth. Clearly, there is a great advantage (energetically speaking) in exploiting solar energy. But the potential importance of chemical sources was also made clear in 1977 when American oceanographers Jack Corliss and Robert Ballard piloted the deep submersible, *Alvin,* to hydrothermal springs on the seafloor located more than 2.4 kilometers (1.5 miles) deep. At this depth, no sunlight exists for photosynthesis, and yet complex ecosystems were found there in which the organisms (including large, multicelled animals) derived their energy entirely from chemical sources provided by the hot fluids. This discovery shocked biologists, as they realized that even though photosynthesis provides much more energy, simple forms of chemical energy are still capable of supporting complex ecosystems. Since 1977, many other examples of deep-sea vent ecosystems have been found in virtually every ocean basin on Earth.

Several impact craters on Mars show evidence of having held lakes at some time in the past. This image of Gusev crater shows the rim of the crater cut by a channel that likely deposited water in the floor of the crater.

A Deep Subsurface Biosphere

As methods of exploration and observation have improved, life's environmental limits have continued to expand. In 1993 American biochemist Thomas Gold suggested that single-celled forms of life survive and grow in the deep subsurface of Earth, residing within tiny pore spaces and fractures in **indurated rocks.** In fact, volumetrically, such subsurface life forms could comprise more than half of Earth's biomass. Microscopic life is also thought to exist in a deep subglacial lake called Vostoc, which lies more than 3 kilometers (1.9 miles) beneath the ice cap of Antarctica. While many subsurface microbes appear to depend on photosynthetically derived organic matter that washes down from the surface, some species can make their own organic molecules from inorganic sources. Called lithoautotrophs (which literally means "self-feeding on rocks"), these organisms use the byproducts of simple weathering processes in which carbon dioxide dissolved in groundwater reacts with rocks to yield hydrogen. Hydrogen in turn is exploited for available energy. These organisms hold special importance for astrobiology because their existence allows the possibility that subsurface life can exist completely independently of surface (photosynthetic) production. Such lifestyles hold important implications for Mars and Europa (one of Jupiter's largest moons), where deep subsurface habitats are postulated to exist.

Studies of **extremophiles** have revealed that terrestrial life occupies virtually every imaginable habitat where liquid water, chemical nutrients, and simple forms of energy coexist. This observation has dramatically expanded the range of habitats available to life as well as the potential for life elsewhere in the solar system or beyond.

Exploring for a Martian Biosphere

Liquid water is unstable in surface environments on Mars today, thus imposing a formidable barrier to the development and survival of Martian life. Nevertheless, models suggest that a global groundwater system could exist on Mars today at a depth of several kilometers below the surface. Indeed,

HOW VIABLE ARE MICROBES UNDER HARSH CONDITIONS?

In addition to an astounding range of ecological adaptations, many microbial species have been shown to survive in a state of stasis under inclement conditions for prolonged periods of time. In even the driest deserts on Earth, some species survive by living inside porous rocks where they find a safe haven from ultraviolet radiation, springing to life only occasionally, when water needed for growth becomes available. An even more interesting example is bacteria that have been germinated from spores preserved in Dominican amber dated at more than 30 million years old. Given this propensity for prolonged survival, the potential for microorganisms to survive under extreme conditions, for example on Mars, has been greatly enhanced.

Clouds and sunlight glint over the Indian Ocean, as seen from the space shuttle Discovety. Liquid water is the basic requirement for life, and Earth's abundant supply supports millions of organisms.

indurated rocks rocks that have been hardened by natural processes

extremophiles microorganisms surviving in extreme environments such as high salinity or near boiling water

biosignatures the unique traces left in the geological record by living organisms

the Viking orbiters revealed many ancient channel features on Mars that formed when groundwater escaped and flooded onto the surface. But could groundwater still exist there today? In 2001 planetary scientists Michael Malin and Kenneth Edgett, using a high resolution camera onboard the Mars Global Surveyor mission, detected more than 140 sites on Mars where water appears to have seeped out of the subsurface, carving small channels in the surface. Under current conditions, average crustal temperatures on Mars are well below the freezing point of freshwater almost everywhere on the surface. Such surface springs of liquid water, however, could be sustained by warm, saline brines (salt lowers the freezing point of water) derived from deep hydrothermal sources. If this hypothesis is proven, the presence of liquid water—even hot, salty water—will substantially enhance the biological potential of Mars.

On Earth, scientists have found fossil **biosignatures** in sedimentary rocks going as far back as there are sedimentary sequences to sample. By studying the processes that govern the preservation of fossil biosignatures in similar environments on Earth, scientists are continuing to refine their understanding of the factors that govern fossil preservation. This provides a basis for the strategic selection of sites on Mars to explore with future landed missions and for sample returns. Due to the lack of plate tectonic recycling and extensive aqueous weathering on Mars, rocks preserved in the heavily cratered, ancient highlands appear to extend back to the earliest history of the planet. The rocks of these old crustal regions could be much better preserved on Mars than they are on Earth. In fact, a meteorite of

SEARCHING FOR LIFE ON MARS

Although present surface conditions on Mars appear unfavorable for life, orbital images of Mars show numerous water-carved channels and possible paleolake basins where water may have once ponded. Geological relationships suggest that during the early history of the planet, liquid water was widespread over the surface. Some scientists have even suggested that during this time a large ocean existed on the northern plains of Mars. Indications are that liquid water disappeared from the surface of Mars about 3 billion years ago, perhaps as a result of gradual losses of the atmosphere by crustal weathering processes (which sequester CO_2 in rocks and soils) and losses to space. If surface life developed on Mars during an early Earth-like period, it quite likely left behind a fossil record. As on Earth, this record should be preserved In ancient, water-formed sedimentary rocks.

Given the complexity and scale of the problem, one cannot expect to land just anywhere on Mars and find evidence of past or present life. The astrobiology community has recommended a phased approach in which global reconnaissance is combined with preliminary surface missions to target the best sites for detailed surface investigations and sample return. The basic goal is to locate sites where there is evidence of past or present water activity and geologic environments that were favorable for the capture and preservation of fossil biosignatures.

In exploring for extant life-forms, there is an interest in finding habitable zones of liquid water in the shallow subsurface that can be accessed by drilling from robotic platforms. This may prove challenging given that models for a groundwater system on Mars suggest that if present, it should be located at a depth of several kilometers, requiring deep drilling technologies that are currently undeveloped. It may actually be simpler to discover a record of ancient life by targeting water-formed sedimentary deposits laid down by ancient hydrothermal systems or in paleolake basins. A key step in implementing this approach is to better understand the mineralogy of the Martian surface. The Thermal Emission Spectrometer instrument began mapping from Mars orbit in 1999 and in 2000 discovered coarse-grained (“specular”) hematite deposits at Sinus Meridiani. Hematite is a form of iron-oxide, which in a coarse-grained form strongly suggests the past activity of water. This site has been targeted for possible landed missions in the future.

Martian origin (ALH 84001), which has been dated at about 4.56 billion years, shows very little evidence of aqueous weathering.

Searching for Life in the Outer Solar System

The discovery that life can survive in deep subsurface environments on Earth, where no sunlight exists, has dramatically reshaped the ways scientists think about the potential for subsurface life on other planets. In the outer reaches of the solar system, energy from sunlight is inadequate to maintain the temperatures required for liquid water at the surface, much less for photosynthesis. However, where internal heat sources exist, liquid water could in principle be present in the subsurface.

Three of the larger satellites of Jupiter (Io, Europa, and Ganymede) appear to possess actively heated interiors that are maintained by gravitational tidal forces. These forces continually distort the shapes of these moons, creating internal friction that is capable of melting rock. In one of Jupiter's satellites, Io, the internal heating is manifested as widespread, active volcanic activity at the surface. On Europa, however, interior heating is manifested in a complexly fractured and largely uncratered (constantly renewed) outer shell of water ice. In many places, blocks of crust have drifted apart and liquid water or warm ice has welled up from below and frozen out in between, forming long, narrow ridges in the spaces between. Over time, some ridge segments have shifted laterally, offsetting older ridge segments along **faults.** Other more localized areas appear to have melted over broad regions and blocks of ice have foundered, tilted, and become refrozen. At an even finer scale, there are smaller, mounded features that are thought to have formed as ice "volcanoes" erupted water or warm ice erupted water from the subsurface.

While the concept of a Europan ocean is still controversial, measurements of the magnetic field of the moon obtained during the Galileo mission have strengthened the case. In order to account for the induced magnetism measured by Galileo, it is likely that a salty ocean exists beneath the water ice crust. (Similar arguments have also been made for two other large satellites of Jupiter, Ganymede and Callisto.) The idea of an ocean of brine beneath the icy crust is consistent with **infrared** spectral data from orbit, which suggest that magnesium and/or sodium sulfate salts are present in surface ices.

In assessing the potential for life on Europa, the presence of liquid water is regarded as crucial, both as a medium for biochemical processes and as a source for the chemical energy necessary to sustain life. There does not appear to be enough solar energy at the surface of Europa to support life. However, in 2001 planetary scientist Chris Chyba proposed a model that predicts that chemical energy sources for supporting life may exist from radiation processing of Europa's surface ice, in combination with the decay of radioactive potassium. Together, these processes could decompose water to hydrogen and oxygen (with the hydrogen escaping to space) and the chemical disequilibrium created potentially exploited for energy by organisms.

LIFE IN A MARTIAN METEORITE?

In 1996 a team of scientists proposed a very intriguing hypothesis regarding the possible biological origin of about a half-dozen features observed in a Martian meteorite, ALH 84001. In part, the hypothesis involved tiny grains of the naturally magnetic mineral magnetite, which is commonly found in basalt (a high-temperature volcanic rock that makes up oceanic crust). While most magnetite on Earth is inorganic, some bacteria have discovered ways to make minute grains of geochemically pure, low-temperature magnetite, which they organize into chains within their cells to use as a kind of directional compass. This enables cells to better control their movement in the environment and to track favorable environmental conditions. Some of the magnetites found in the Martian meteorite bear a strong resemblance to the magnetites formed by terrestrial bacteria. But is the population *of* magnetites in the meteorite a reliable indicator of life? Scientists are still debating this question.

fault a fracture in rock in the upper crust of a planet along which there has been movement

infrared portion of the electromagnetic spectrum with waves slightly longer than visible light

extrasolar planets planets orbiting stars other than the Sun

Habitable Environments Beyond the Solar System

The discovery of planets orbiting other Sun-like stars in the galaxy is a key scientific discovery that has played a central role in the astrobiological revolution. The original discoveries, made in the mid-1990s, have continued. By the early twenty-first century, **extrasolar planets** have been found orbiting almost seventy solar-mass stars in the nearby region of the galaxy. Six of these discoveries are of planetary systems with two or more planets. Present discovery methods are based on the detection of a slight shift or "wobble" in the position of the star that results from the gravitational pull of an orbiting planet(s). With existing technologies, this method allows for the detection of planets that are Jupiter-sized or larger. Some of the extrasolar planets detected occupy orbits within the habitable zone where liquid water could exist. Gas giants (such as Jupiter and Saturn) are planets that lack a solid surface, but they could contain interior zones of liquid water, or might have large (undetectable) satellites with solid surfaces and liquid water. These discoveries have revealed planets around other stars to be commonplace in the Milky Way, thus widening the possibilities for life elsewhere in the cosmos. SEE ALSO EXTRASOLAR PLANETS (VOLUME 2); JUPITER (VOLUME 2); MARS (VOLUME 2); MARS MISSIONS (VOLUME 4); PLANETARY PROTECTION (VOLUME 4); SCIENTIFIC RESEARCH (VOLUME 4); SETI (VOLUME 2); TERRAFORMING (VOLUME 4).

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EXPLORING EUROPA

The next Europa mission, planned for launch sometime after 2009, is expected to carry high-resolution spectrometers to map the surface and determine the mineralogical and organic composition of the surface ice. In addition, radar sounding will be used to probe the subsurface from orbit in search of zones of liquid water. This will allow a more thorough test of the hypothesis of a subsurface ocean and help identify the best sites for surface exploration. If a subsurface ocean is in fact found, the next step could be to send robotic landers to search for biosignatures preserved in the ice. Eventually we may be able to deploy small "cryobots" that would melt their way through the ice, deploying minisubmarines to explore for signs of life or organic chemistry.

Biotechnology

Biotechnology research in space is predicated on understanding and exploiting the effects of the unique **microgravity** environment on chemical and biological systems. The results of these experiments could point the way not only to commercial enterprises in space but also to new research directions for laboratories on Earth. Protein crystallization and cell biology are two areas in which microgravity research is particularly promising.

microgravity the condition experienced in freefall as a spacecraft orbits Earth or another body; commonly called weightlessness; only very small forces are perceived in freefall, on the order of one-millionth the force of gravity on Earth's surface

Protein Crystallization

Researchers are interested in determining the structure of proteins because the twists and folds of these complex molecules provide clues to their specific functions and how they have evolved over time. However, for scientists to study their structures, the molecules must be "held in place" through crystallization. Large, good-quality crystals are valued by structural biologists, but some organic molecules are easier to crystallize than others are. In some cases the resolution of important biological questions awaits the ability to produce adequate crystals for structural analysis.

For more than fifteen years it has been known that with other conditions being equal, protein crystals grown in a microgravity environment are