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Why Life Might Be Widespread in the Universe

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> The fact that this chain of life existed in the black cold of the deep sea and was utterly independent of sunlight— previously thought to be the font of all Earth's life—has startling ramifications. If life could flourish there, nurtured by a complex chemical process based on geothermal heat, then life could exist under similar conditions on planets far removed from the nurturing light of our parent star, the Sun. —Robert Ballard, *Explorations*

Several miles beneath the warm, life- and light-filled surface regions of the world's oceans lies a much harsher environment, the deep sea floor. Vast regions have little oxygen. There is no light. Much of this sea floor is composed of nutrient-poor sand, mud, or slowly precipitated manganese nodules. Temperature is a fraction above the freezing point. At least 6000 pounds of water pressure crush each square inch of matter at even average ocean basin depths. Because of these factors, except for small populations of highly specialized creatures that depend for food on the slow rain of detritus from far above, most of the deep-ocean bottom is a biological desert, long thought to be virtually lifeless and monotonous terrain.

Yet one type of environment found on the bottoms of all of Earth's oceans is neither flat nor sparsely populated. Running in linear ridges extending for thousands of miles along the sea floors are chains of active volcanic vents called deep-sea rifts. These rifts, which are situated along the margins of the great oceanic plates that make up the rocky base of the ocean floor, form undersea mountain chains. Here, in the great depth, darkness, and pressure of the sea, new crust is being created every hour, upwelling from below. These are places where the sea floor literally pulls away from itself, spreads, and in the process creates, in the endless, frigid night of the sea floor, the slow motion of tectonic plate movement known as continental drift. It seems the least hospitable environment on planet Earth. Ironically, it is teeming with life.

Amid constant earthquakes, hot magmatic lava wells up from subterranean regions in these rifts, where it encounters frigid sea water. Great gouts of this brimstone are instantly quenched as they meet the cool sea water, producing grotesque, pillow-like shapes as they turn to black rock. It is a place like no other on Earth, a region of unbelievable extremes where 2000°F lava meets 32°F water under a pressure of 400 atmospheres 2 miles beneath the sea. It is a zone of high-energy violence, where torrents of mineralized water flow like rivers out of the underworld, building great columns of metal precipitate from the hellish brew bubbling out of the Earth. Yet amid this deep-sea inferno, another and most curious phenomenon exists: submarine snow. Not the gentle snow that falls on land, but a blizzard of white material that flows out of the submarine fissures and then slowly settles onto the gnarled sea bottom. This “snow” is actually life, flocculated globs of microbes numbering in the billions and living amid the heat and poison spewing out of the vents. In utter darkness, unseen by any eye until a few humans probed the abyss in tiny, deep-diving submarines, life silently exists and thrives, creating this ethereal snowfall.

LOVERS OF THE EXTREME

The environments around the deep-ocean volcanic rifts can be described with a single word: extreme. Extreme heat, extreme cold, extreme pressure, darkness and toxic-waste waters are conditions seemingly inhospitable to every living thing. Yet over the past two decades, oceanographers and biologists who have braved the perils of the long trip to this depth in their small submarines have made stunning discoveries. The finding of bizarre tubeworms and clams was completely unexpected, but even this life is conceivable to us, for it exists in the warmed waters around the volcanic vents. What was not expected, however, was that life could live not only around, but also amid, the vents. Within these scalding cauldrons of superheated water, a rich diversity of microbial entities grow and thrive at temperatures far too hot for any animal. Yet here, indisputably, is life, in a region previously thought as sterile as Mars.

It is just such environments on Earth that may hold the most important clues to the possibility of extraterrestrial life on a place such as Mars. If the harsh hydrothermal vents can harbor life, why not the inhospitable habitats of Mars, or Europa (a moon of Jupiter), or unnumbered planets farther away as well? Life *does* exist in the hydrothermal vents of the deep sea, just as it does in other seemingly sterile habitats where organisms have recently been discovered, such as deep underground in cold basalt, in sea ice, in hot springs, and in highly acidic pools of water. Because of *where* they live, the microorganisms in these uninviting places have been dubbed *extremophiles,* “creatures that love the extreme.”

The discovery that life is abundant and diverse in extreme environments is one of the most important of the Astrobiological Revolution. It gives ushope that microbial life may be present and even common elsewhere in the solar system and in our galaxy, for many environments on Earth that are now known to bear extremophile life are duplicated on other planets and moons of the solar system.

The majority of research on extremophiles has centered on two types of habitats: the undersea hydrothermal vents described above and the terrestrial equivalents of the hydrothermal vents: geysers and hot pools on land. Volcanic processes create both of these habitats, and accordingly, they provide windows into the deep Earth. Life is tougher than we thought. If bacteria-like organisms can inhabit high-temperature geysers, they can live deep in Earth's crust in the subterranean blackness and heat of the underworld. The deep-ocean hydrothermal vents, and the hot springs and geysers of volcanic regions on land, are places where these previously unknown, deep-Earth assemblages of microbes can be observed and sampled. And they may also offer windows into regions where extraterrestrial life may exist on other planets and moons.

The first extremophiles were discovered not in deep-sea settings but in the geysers of Yellowstone National Park. There, in the early 1970s, microbiologist Thomas Brock and his colleagues discovered "thermophilic" extremophiles, microbes capable of tolerating temperatures in excess of 60°C, and they soon thereafter recovered microbes that could live at 80°C. Since then a variety of such extreme-heat-loving microbes have been isolated from hot springs at many localities around the world. Until that time it was believed that *no* life of any sort could live at temperatures much above 60°C, just as it is still believed that no *multicellular* organisms (such as animals or complex plants) can tolerate temperatures above 50°C. Yet, many hot springs extremophiles thrive in temperatures above 80°C, and some can live in temperatures above that of boiling water, 100°C. In contrast, the majority of bacteria grow best at 20–40°C. Discovery of these hot springs extremophiles inspired the search for similar microbes in the deep-ocean hydrothermal settings.

The deep-sea vents are characterized by three conditions previously considered deleterious to life: high pressure, high heat, and lack of light. Because of the great pressures encountered deep in the sea, water can be heated well past its boiling point at Earth's surface. The highest temperatures encountered in these environments can exceed 400°C. When this superheated, mineral-rich water hits the near-freezing sea water surrounding the vents, it is rapidly cooled, although extensive zones of water well above 80°C are found around the vents.

The submarine hydrothermal vent systems cover enormous lengths of the sea floor and may be one of the most unique habitats on Earth. However, they were virtually unknown before the 1970s because of their remoteness and depth. Since the advent of deep-diving submarines such as *Alvin,* these habitats have been intensively studied. The water near the vents, once thought too hot for life, is now known to be inhabited by a diversity of microbial life, which appears to provide food for a whole host of larger organisms living around the vents. The abundant microbes thus form the base of a deep-sea food chain that requires neither light nor photosynthesisers such as plants. Most ecosystems we are familiar with have, at the base of their food chain, organisms that take carbon dioxide and light and produce living cells through photosynthesis. Light is thus the energy source that allows growth. Many of the extremophile bacteria have no need for light. They derive their energy from the breakdown of compounds such as hydrogen sulfide and methane, which fuels their metabolism. Furthermore, these organisms evolved early in earth history, and this suggests that the earliest life on our planet—and by inference on other planets as well—may be chemically fueled rather than powered by light. The implication is that light may not be a prerequisite for life.

Perhaps the most unexpected aspect of these discoveries was that many of the bacteria in these regions not only support, but also demand and thrive on, temperatures above 80°C. One species discovered in the deep-sea hydrothermal vents reproduces best in water at temperatures above 105°C and remains able to reproduce in water as hot as 112°C.

Even more startling lovers of extreme heat have recently been found in these environments. In 1993, John Baross and Jody Deming of the University of Washington published a paper entitled "Deep-sea smokers: Windows to a subsurface biosphere?" In this paper, the two oceanographers advanced the idea that the interior of Earth is home to microbes capable of living, under high pressure, at temperatures above that of boiling water—as much as 150°C. They called these organisms "super thermophilic." This bold prediction was supported when John Parkes of Bristol, England, discovered intact microbes at 169°C in a deep-sea drill core. What is the upper temperature limit for life? Microbiologists now theorize that life may be able to withstand 200°C in high-pressure environments.

Although some of them fall within the taxonomic group formally called Bacteria, the majority of these extremophilic microbes belong to the taxonomic group known as Archaea. The archaea are biological stalwarts indeed. They thrive in boiling water and live on elements toxic to other life, such as sulfur and hydrogen. The discovery of this major group of living organisms itself precipitated one of the great revolutions in biology, for their existence required a substantial reconfiguring of the time-honored model we can call the "Tree of Life," the theorized evolutionary pathway leading from the earliest life to the most complex.

THE ARCHAEANS

Biologists have long recognized that species can be grouped into hierarchical assemblages. These units are linked by lines of descent; that is, all species that make up a higher category share a common ancestor. Species are grouped into genera. (Our species is grouped, along with the extinct human forms, into the genus *Homo*. This means that all species of *Homo,* including *Homo sapiens, Homo erectus,* and *Homo habilis,* among others, have a common ancestor.) Genera are grouped into families, families into orders, orders into classes, classes into phyla, and phyla into kingdoms. The kingdoms have always been defined as the highest level, so they are not grouped into any higher unit. The earliest practitioners of this system, which was developed by the great Swedish naturalist Carl Linnaeus in the eighteenth century, first recognized only two king doms: animals and plants. As biologists invented and mastered microscopes and came to understand plants better, they increased the number of kingdoms to five: the kingdoms Animalia, Plantae, Fungi, Protozoa, and Bacteria. But the discovery of the archaea changed all of that. They are so different that they have required scientists to devise an entirely new taxonomic category of life.

The archaea have long been overlooked because they closely resemble bacteria. But once molecular biologists were able to analyze their DNA, it became clear that these tiny cells were as different from bacteria as bacteria are from the most primitive protozoans. This led University of Illinois biologist Carl Woese to propose a new category of life, the *domain,* which he placed above kingdoms. In this scheme, the five kingdoms are spread over three domains: Archaea, Bacteria, and a new category called Eucarya, which includes the plants, animals, protists, and fungi.

The domain Archaea is itself subdivided into two previously unrecognized kingdoms: the kingdom Crenarchaeota, made up of heat-loving forms, and the kingdom Euryarchaeota, which includes a few thermophiles but is composed mainly of forms that produce the organic compound methane (swamp gas) as a biological by-product of their metabolism. Most archaeans are “anaerobic”; they can live only in the absence of oxygen. This characteristic makes them prime candidates for the first life on Earth, because the newly formed Earth had no free oxygen.

Although many types of archaeans have been found in hot-water settings, it is clear that they can live in other subterranean settings, including within solid rock itself. The first clue that life might exist hundreds to thousands of meters below Earth's surface came in the 1920s, when geologist Edson Bastin of the University of Chicago began to wonder why water extracted from deep within oil fields contained hydrogen sulfide and bicarbonates. Bastin knew that both of these compounds are commonly created by bacterial life, yet the water coming from the oil wells was from environments that seemed far too deep and hot to support any sort of bacterial life discovered up to that time. Bastin enlisted the aid of microbiologist Frank Greer, and together they succeeded in culturing bacteria recovered from this deep water. Regrettably, their findings were dismissed by other scientists of the time as being due to contamination from the oil pipes, and this first interdisciplinary venture linking the fields of geology and microbiology languished, its provocative discovery ignored for more than 50 years.

The possibility that life was present deep within our planet was finally taken seriously when scientists began studying groundwater around nuclear waste dumps in the 1970s and 1980s. As ever-deeper boreholes were drilled, microbial life was routinely found at depths long thought to be too great to support life of any kind. But were the microbes found at these depths actually living there, or were they contaminants from surface regions that were picked up by the sampling equipment on its journey down? This question was not answered until 1987, when an interdisciplinary team of scientists assembled by the United States Department of Energy built a special coring device capable of drilling deep into the rock and extracting samples with no possibility of contamination. Three 1500-foot-deep boreholes were drilled at a government nuclear research laboratory near Savannah River, South Carolina. Samples brought to the surface were analyzed for microbes, and it was quickly discovered that microbial life did indeed exist at these depths and that it was rich in both number of species and number of individuals. A new habitat for life had been discovered, and the pioneering work of Bastin and Greer had been confirmed.

It is generally acknowledged that the cataloguing of Earth's species is far from complete—that many species of all groups of life, not just extremophiles, wait to be discovered. Less well known is that our understanding of the *habitats* occupied by life on this planet may be equally incomplete; the new extremophile discoveries beneath Earth's surface are proof of that. In this age of satellite surveys and global travel, it seems incongruous that there could be vast unexplored regions harboring unknown life, but this is certainly the case. Aside from Jules Verne's imaginative and prophetic novel *Journey to the Center of the Earth,* humankind has little penetrated the last frontier and the region that may hold the single largest mass of life inhabiting the planet: deep in Earth's crust.

With the discovery of deep life in South Carolina, many teams began probing ever deeper underground, trying to find the lower limit of life within the crust of Earth itself. Soon they learned that subterranean microbes could be found in most geological formations; the deep bacterial and archaean world thus appears ubiquitous under the surface. The greatest depth from which these life forms have so far been recovered is about 3.5 kilometers, at temperatures of 167°F. At such great depths, however, the population density of the microbes is low. They can live in many rock types, including both sedimentary and igneous rocks. Temperatures increase in a planet as one descends deeper into the crust. Archeans may inhabit a wide range of rock types even several miles beneath Earth's surface. Cornell University geologist Thomas Gold has gone so far as to suggest that the combined biomass of microorganisms beneath Earth's surface may be several times that of *all* organisms—great and small, complex and simple—living on the surface above. If so, microorganisms are by far the most numerous organisms on Earth!

The maximum depth at which extremophiles have been found to live is constantly being revised. In 1997 the record was 2.8 kilometers, but soon a mine located in South Africa yielded specimens from a depth of 3.5 kilometers. The basic requirements of the inhabitants of this “deep biosphere” are water; pores, in the source, of sufficient size to allow the presence of the deep microbes; and nutrients. Because the extremophiles are adapted for pressure they are virtually unaffected by the high pressures encountered at these great depths.

The nutrients used by these deep-living extremophiles come from the rocks they live in. In sedimentary rock, nutrients derive from organic material trapped at the time of the rock's deposition. The deep-biosphere microbes (the microbes living in sedimentary rock) then utilize this material for the energy and organic matter necessary for life. Oxidized forms of iron, sulfur, and manganese are also utilized as nutrients. Living in sedimentary rock thus poses no great hardship for certain archaeans and bacteria. Living in igneous rock, however, is a more difficult proposition.

Igneous rock, such as basalt (the rock that forms when lava cools and solidifies) has no (or very little) constituent organic matter. It was therefore a major surprise when scientists in Washington state discovered flourishing communities of microbes living in ancient basaltic rock in the Columbia River basin. Microbiologists Todd Stevens and James McKinley from Batelle Laboratory discovered in the 1980s that many of the bacteria they found in these rocks were manufacturing their own organic compounds, using carbon and hydrogen taken directly from hydrogen gas and carbon dioxide dissolved in the rock. They produced methane as a by-product of their synthesis, so they acquired the name methanogens. These archaea are thus autotrophs, organisms that can produce organic material from inorganic compounds. Cooccurring heterotrophic or organic-consuming microbes then ingest some of the organic material produced by these autotrophic organisms. This is (like the deep-sea vent community) an ecosystem totally independent of solar energy—independent of the surface and of light. These particular communities have been dubbed—perhaps appropriately—the SLiME communities, for “subsurface lithoautotrophic microbial ecosystem.” Because their presence in these dark, sometimes hot regions of Earth's crust tells us that sunlight is not necessary to sustain life, their discovery is one of the most important ever made about the range of environments that can support life. It means that even a far-distant and relatively cold planet such as Pluto could conceivably support life in the warm, inner portions of its crust. Planets and moons far from a star may have frigid surfaces, but their interiors are warm with heat from radioactive decay and other processes.

The deep-rock microbe communities can be trapped within their host rock for millions of years. They first get into the igneous rock via flowing groundwater, but in some instances this groundwater is cut off, and yet the deep microbes persist and thrive. Samples from the Taylorsville region of Texas are thought to be 80 million years old and have grown and evolved at exceedingly slow rates. They became trapped in the hard igneous rock during the heyday of the dinosaurs and remained there, living without any contact with the rest of Earth's life, until humans released them by digging deep wells. Some of these microbes have adapted to very low levels of nutrients and tolerate extended periods of starvation.

Extremophiles are not only adapted to hot and high-pressure conditions. Other groups are found in conditions thought too *cold* for life. All animal life eventually ceases at below-freezing temperatures. When the bodies of animals are cooled below the freezing point, they can enter a state of suspended animation, but the metabolic functions do not continue. Some extremophiles, however, circumvent this. Microbiologist James Staley of the University of Washington discovered a new suite of extremophiles living in icebergs and other sea ice. This habitat was long considered too cold to harbor life, yet life has found a way to live in the ice. This particular finding is as exciting and as relevant to the astrobiologist as the heat-loving extremophiles, for many places in the solar system are locked in ice. Other extremophiles relish chemical conditions inimical to more complex life, such as highly acidic or basic environments or very salty seawater.

The Martian Connection

The interest in extremophilic microbes intensified after the discovery of the now-famous Martian meteorite known as ALH 84001, a hunk of rock found in the Allan Hills region of Antarctica on December 27, 1984. After it was discovered, this piece of cosmic slag was filed away and forgotten for a decade. It was finally reexamined, however, and determined to be from Mars. A team of NASA scientists then began to probe it, and their examination culminated in the stunning announcement on August 7, 1996, that this particular piece of rock might contain fossils of Martian microbes in its stony grasp.

Of the various lines of evidence used by NASA scientists to arrive at this startling conclusion, the most fascinating were small rounded objects in the meteorite resembling fossil bacteria. And why not? Conditions on the Martian surface today are highly inimical to life: subject to harsh ultraviolet radiation, lack of water, numbing cold. The Mars Pathfinder expedition only seemed to confirm the planet's inhospitality—even for the highly tolerant extremophilic microbes. But what of the Martian *subsurface?* Perhaps life still exists in the subterranean regions of Mars, where hot hydrothermal liquid associated with volcanic centers could create small oases, a Martian equivalent of Earth's deep biosphere, replete with archaeans.

And even if life is now totally extinct on Mars, what of its past? Since the Viking landing of 1976, scientists have known that the ancient Mars had a much thicker atmosphere and had water on its surface, at least for a brief period of time. Three billion years ago, Mars could have been warmer because of its cloaking atmosphere. Such conditions still would have been too harsh for animal life, but judging from what we now know about the extremophiles on Earth, the early Martian environment would have been quite conducive to colonization by microbes. The extremophiles need water, nutrients, and a source of energy. All would have been present on Mars. It may be that life does not exist on Mars today. Yet there may be a great deal that we can learn about ancient Mars in its fossil record—a fossil record perhaps populated by Martian analogs to Earth's extremophiles. Andrew Knoll of Harvard University has pointed out that for very old rocks, the fossil record may be fuller on Mars than it is on Earth, because there has been little erosion or tectonic activity on Mars to erase the billions of years of fossil records. Knoll has even told us where on Mars to search for fossils: on an ancient volcano named Apollinaris Pater, whose summit shows whitish patches interpreted to be the minerals formed by escaping gases, or in a place called Dao Vallis, a channel deposit on the flank of another ancient volcano where hot water may have flowed out from a hydrothermal system within the Martian interior. Mineral deposits there might yield a rich fossil record of ancient Martian extremophiles.

IMPLICATIONS FOR THE "HABITABLE ZONE"

The discovery of extremophilic life lends major support to the first part of the Rare Earth Hypothesis. The almost ubiquitous presence of extremophiles on Earth in regions previously thought too hot, cold, acidic, basic, or saline shows that (at least in microbial form) life can exist in a much wider range of habitats than previously thought. This is the strongest evidence that life might be widespread in the Universe (and thus perhaps widespread in the solar system). But there is a second major implication of the discovery of extremophiles: They show that life can exist well above and below the temperature range (32–212°F) that allows for the existence of liquid water at a pressure of 1 atmosphere, the conditions found in what has been called the *habitable zone*. The extremophiles have rendered the original concept of the habitable zone obsolete. In our solar system, surface water exists only on Earth (and perhaps on Europa), so if we assume that we will find life only on planets with water, then we would have to conclude that only these two bodies should harbor life of any sort. The discovery of the extremophiles requires us to revise that thinking. Let us keep this in mind as we examine, in Chapter 2, the concept of habitable zones.

Chapter 1. Why Life Might Be Widespread in the Universe

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