Extreme organisms on Earth show us just how weird life elsewhere could be. by Chris Impey

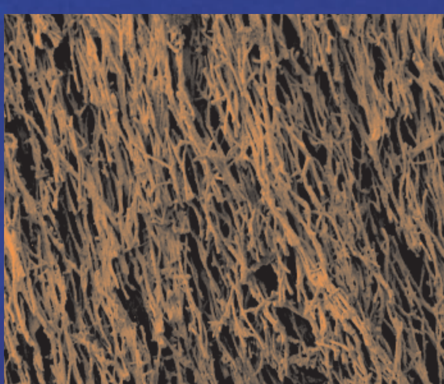
How **life** could thrive

Humans have left their mark all over Earth. We're proud of our role as nature's generalists — perhaps not as swift as the gazelle or as strong as the gorilla, but still pretty good at most things. Alone among all species, technology has given us dominion over the planet. Humans are endlessly plucky and adaptable; it seems we can do anything.

Yet in truth, we're frail. From the safety of our living rooms, we may admire the people who conquer Everest or cross deserts. But without technology, we couldn't live beyond Earth's temperate zones. We cannot survive outside for long below freezing or above 104° Fahrenheit (40° Celsius). We can stay under water only as long as we can hold our breath. Without water to drink we'd die in 3 days.

Microbes, on the other hand, are hardy. And within the microbial world lies a band of extremists, organisms that thrive in conditions that would cook, crush, smother, and dissolve most other forms of life. Collectively, they are known as extremophiles, which means, literally, "lovers of extremes."

Extremophiles are found at temperatures above the boiling point and below the freezing point of water, in high salinity, and in strongly acidic conditions. Some can live deep inside rock, and others can go into a freeze-dried "wait state" for tens of thousands of years. Some of these microbes harvest energy from methane, sulfur, and even iron.



Silica minerals coat bacterial filaments in a sample from the Grand Prismatic Spring in Yellowstone National Park. Scientists hunting for martian microorganisms could search for similar structures in fossilized hot spring deposits. Arizona State University/Jack Farmer

The study of extremophiles has taught scientists that life has evolved on Earth to colonize even the most inhospitable environments. And if they can do it here, why can't they do it out there — in the extremes of cold, pressure, and radiation beyond Earth?

As NASA prepares to spend billions on the search for life in the solar system, it's worth recalling the exotic and weird life right under our noses. We have much to learn from extremophiles that could assist and inform the search for life elsewhere.

Extreme origins

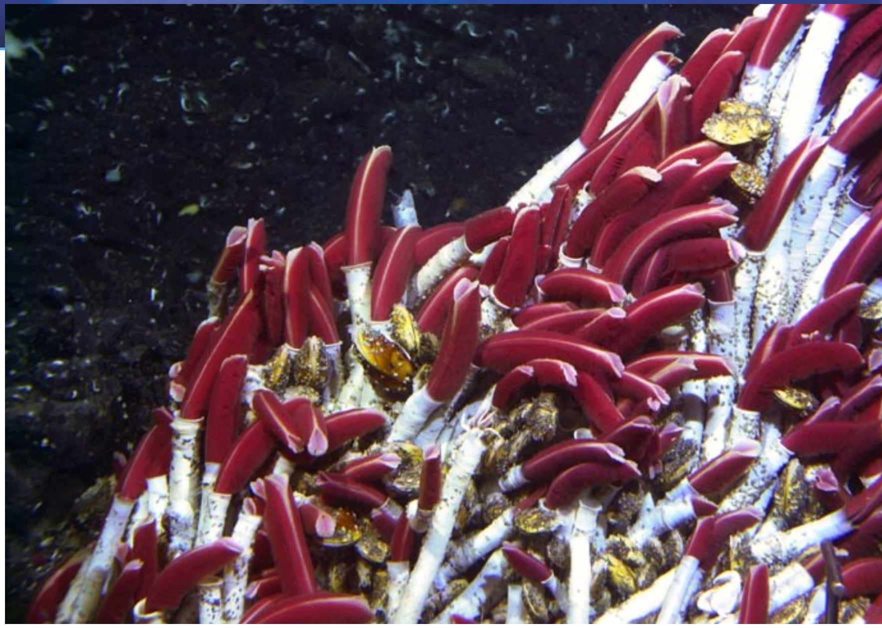
Earth is a microbial planet, and the common ancestor of all life on Earth

on **hostile** worlds

In the steaming hydrothermal waters of Yellowstone National Park's Grand Prismatic Spring, scientists found Strain 121 (inset), the first known extremophile. This heat-tolerant bacterium can survive at temperatures up to 250° Fahrenheit (121° Celsius). The orange fringes around the pool are mats of algae and bacteria living on energy and minerals in the water.

Jim Peaco (NPS)/Inset: Derek R. Lovley

Background montage *Astronomy:* Kellie Jaeger



The deep-sea tube worms in this image live on hydrothermal vents along the Pacific Ocean's Galápagos Rift. The worms live symbiotically with bacteria in their guts: The bacteria use hydrogen sulfide gas spewing from the vents as a source of energy and, in the process, make carbohydrates for the worms. Woods Hole Oceanographic Institution

was probably a heat-loving extremophile. When scientists resurrected proteins from these ancestral bacteria for study in the lab, the organisms performed best at a sizzling temperature of 150° F (65° C).

Early Earth was as hostile and inhospitable as Dante's hell. Visualize lightning, steam, a rain of meteorites, and a surface covered with magma and sulfur. This doesn't exactly bring to mind Darwin's "warm little pond."

Think of extremophiles as stouthearted little biological superheroes, doing heroic jobs under nearly impossible conditions. If it helps, imagine them clad in tiny masks and capes and booties, though in practice most of them are nearly spherical and unexceptional in appearance.

The names of extremophile categories convey their particular characteristics, so they're not quite as catchy as the names of comic superheroes. There's Thermophile, who emerges from the boiling inferno unscathed. There's Psychrophile, who shrugs off extreme cold. There's Endolith, who does his best work encased in rock. There's Acidophile, who energizes by bathing in battery acid. And there's Barophile, who withstands pressures that would bring lesser superheroes to their knees.

Extremophiles were first discovered in the hot springs of Yellowstone National Park just over 40 years ago. Yellowstone is still the prototypical site for the study of microbes with resistance to high temperature and acidity.

As the temperature of water rises, most life gets into trouble. At 104° F (40° C), oxygen won't dissolve well in water, so organisms like fish will die. Above 167° F (75° C), chlorophyll breaks down, making photosynthesis impossible. Above 212° F (100° C) — the boiling point of water at sea level — cells normally can't control the flow of molecules in and out. At boiling, the complex shapes of DNA and proteins unfold and no longer function.

Tardigrades, a group of tiny organisms called water bears, include some 1,000 species and live in the most extreme environments on Earth. This member of a class of tardigrades, Macrobiotus tonollii, hails from Roan Mountain, Tennessee. Diane R. Nelson

With certain extremophiles, high temperatures are less of a challenge. The reigning champion thermophile, dubbed Strain 121, continues to grow when it's as hot as 250° F (121° C). Extremophiles near deep-sea hydrothermal vents might even withstand superheated water over 390° F (200° C), although this is still unconfirmed.

Thermophiles survive by reaching deep into the chemical toolbox for adaptive strategies. For example, they use only the sturdiest enzymes, they ingest salts that shield the DNA double helix, and they incorporate saturated fats to bolster their cell membranes.

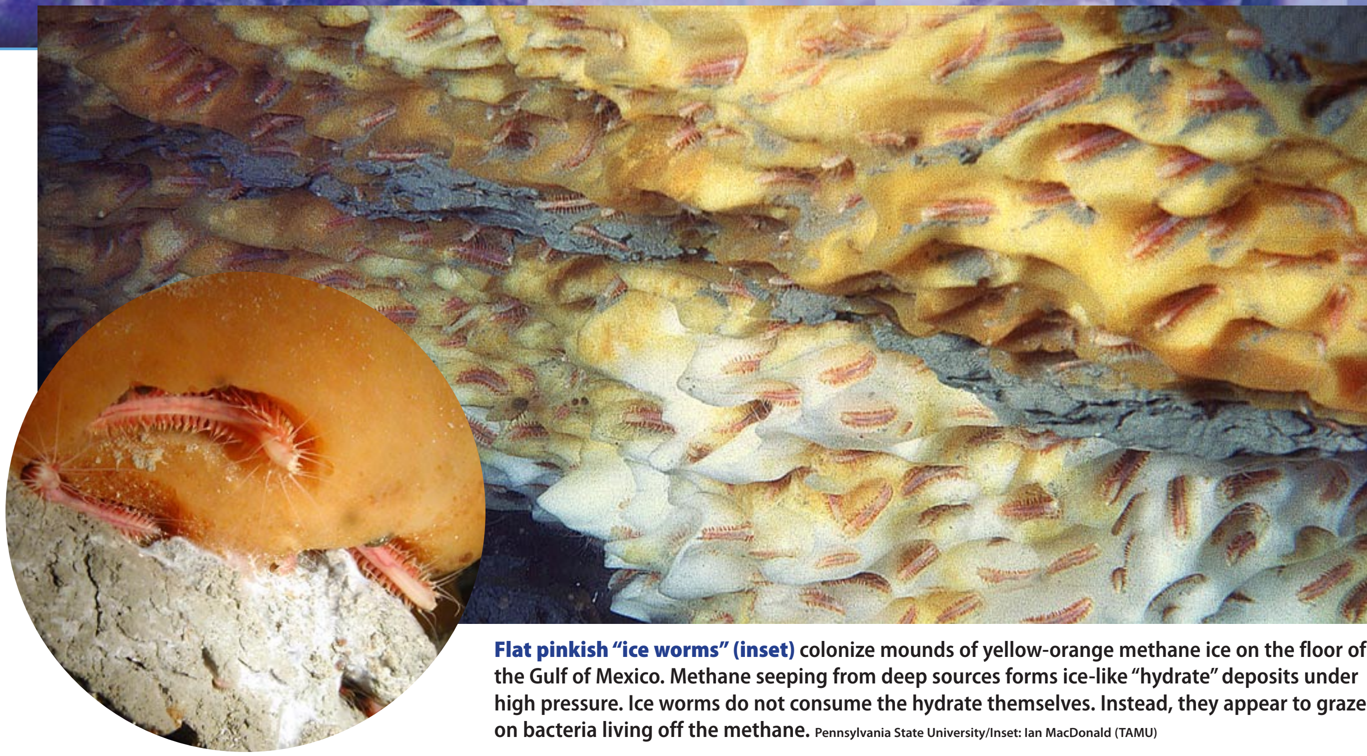
Heat tolerance is a legacy of the conditions on early Earth. These deep-sea survivors could ride out the heavy meteorite bombardment that wreaked havoc with surface dwellers early in Earth's history.

The big chill

At low temperatures, chemical reactions slow down and life gets sluggish. When water freezes, it expands by 10 percent and causes cells to rupture. Yet there is a type of nematode — tiny, wormlike creatures — that can survive even being frozen.

Organisms ranging from microbial colonies to the tiny insect called a Himalayan midge remain active down to –0.4 F° (–18° C). Some organisms do it by insulating themselves from the external environment with fat-soluble molecules called lipids. Others take in salts that act like antifreeze. Many cell lines remain viable but inactive in liquid nitrogen at –320° F (–196° C).

Biodiversity in the coldest parts of the world is amazing. In polar regions, algae are so numerous they often color the ice green. Tiny, swimming crustaceans called krill outweigh the combined bulk of all humans on the planet.



Flat pinkish "ice worms" (inset) colonize mounds of yellow-orange methane ice on the floor of the Gulf of Mexico. Methane seeping from deep sources forms ice-like "hydrate" deposits under high pressure. Ice worms do not consume the hydrate themselves. Instead, they appear to graze on bacteria living off the methane. Pennsylvania State University/Inset: Ian MacDonald (TAMU)

We think water is essential for life, yet some organisms survive with surprisingly little of it. Chile's Atacama Desert and Antarctica's high valleys are so dry they're a perfect lab for scientists who test-drive equipment and experiments intended for Mars. Yet a small variety of lichens and insects survive in these arid environments, where it may not rain for decades at a stretch.

Making do with little is one thing, but there's another strategy when the drying is total. Rather than just giving up, organisms maintain a breezy optimism by going into hibernation. Some spores and cysts appear to be able to survive for a million years in suspended animation, and bacteria manage the same trick when they're trapped in salt crystals. To reanimate, just add water!

Living under pressure

Pressure is also no problem for creatures that have adapted to it. Finding life in the deep sea has strongly influenced thinking about extremophiles beyond Earth because their discovery was so unexpected. For this, we can thank a submersible called Alvin.

Alvin is the size of a small SUV and cruises at a plodding 1 knot (1.2 mph), but its titanium hull can withstand the mountainous weight of an entire ocean. In 1977, Alvin's crew discovered hydrothermal vents off the Galápagos Islands at a depth of 1.6 miles (2.5 kilometers).

The crew was amazed to find a thriving ecosystem that lived without solar energy. Three hundred species congregated near superheated water from "black smoker" vents. The creatures ranged from bacteria and iridescent shrimp to giant clams and 6-foot-long (2 meters) red-tipped worms. The base of this ecosystem consists of bacteria living off hydrogen sulfide gas spewing from the vents.

Recent discoveries add the important information that not all life on the deep seafloor requires hydrothermal heat. For example, pink "ice worms" burrow into mounds of ice-like methane hydrate on the floor of the Gulf of Mexico, possibly feeding on methane-metabolizing bacteria.

Titans of toxicity

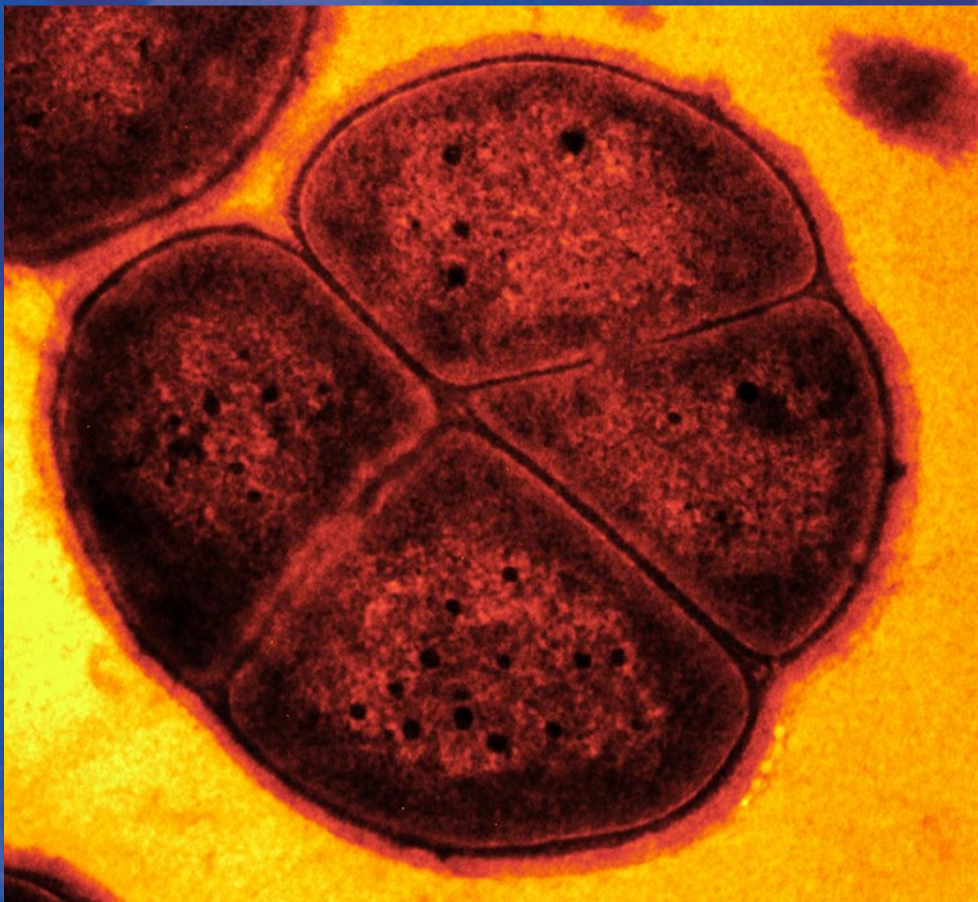
Extremophiles can also tolerate lethal chemical conditions. If you were adrift at sea in a small boat with no supplies, you might just get desperate enough to drink seawater. And you would die. Seawater causes dehydration by increasing the pressure inside cells. Water exits through cell membranes, and the DNA inside breaks down.

But salt-loving microbes make their homes in salt flats, inland seas, and briny pools on the seafloor. They use charged molecules (ions) and simple sugars to protect their cell functions. Algae called Dunaliella salina handle salinity 10 times that of seawater. Beyond this concentration, salt actually precipitates out of solution.

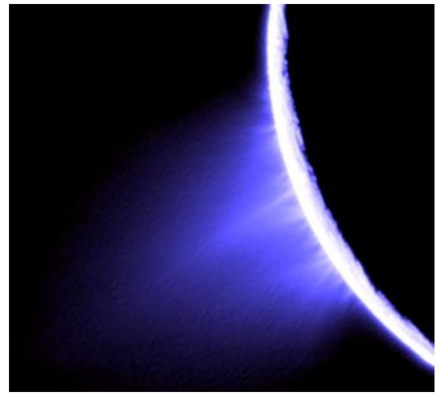
Extremophiles also push the edges of the 14-point pH scale, which describes the concentration of hydrogen ions in a solution. This is important for biological processes because hydrogen ions' electrical charge drives chemical reactions. The pH of pure water is 7, and our cells can't stray far from this without serious dysfunction. A substance with a pH below 7 is an acid; a substance with a pH above 7 is a base.

Acid test

Miners first worked the The Iron Mountain mine near Mount Shasta in Northern California in the 1860s gold rush. It has since become one of the U.S. Environmental Protection Agency's worst toxic sites. When pyrite minerals (iron sulfide) in mining waste rock interact with water and oxygen, they produce sulfuric acid. The acid runoff has, in turn, leached out heavy metals like arsenic, cadmium, and zinc.



In this scanning-electron microscope image, four individual bacteria form a "tetrad" of the species Deinococcus radiodurans. The microorganism's talent for fast DNA repair allows it to withstand radiation levels that would quickly extinguish most other Earth life. Michael J. Daly (UHSUHS)



Cassini Orbiter flybys of Saturn's moon Enceladus revealed watery geysers spewing from fractures. The water temperature, at 32° Fahrenheit (0° Celsius), is potentially more hospitable to life compared to Enceladus' surface, which plunges to –328° F (–200° C). Could the geysers' hydrothermal source serve as a moist refuge for saturnian extremophiles? NASA/JPL/SSI

But Ferroplasma acidarmanus likes it there just fine. This microbe is a member of the Archea, Earth's earliest forms of life. It grows best at an acidic pH of 1 and a temperature of 240° F (115° C). For comparison, consider that lime juice has a pH of 2, similar to vinegar. But F. acidarmanus can even tolerate a pH of 0 — battery acid. It does this by using protons in an electrical balancing act that fends off the worst effects of acidity within the cell.

Some organisms have adapted to multiple environmental extremes. Meet Bacillus infernus, the "bacillus from hell," which withstands a combination of great heat, pressure, and acidity. This hardy microbe turned up in a deep-drilling project in Virginia. B. infernus lives in rock several miles underground, where the pressure is hundreds of times greater than on Earth's surface.

So far below the surface, an organism is detached from the conventional biosphere. It exists independently of the Sun's rays, doesn't use photosynthesis, and doesn't consume the organic material from other formerly living organisms. Life is hard when you live in rock, so B. infernus divides only about once every thousand years.

Now meet Deinococcus radiodurans, "Conan the Bacterium," which can tolerate radiation thousands of times more intense than a dose that would kill a human. Inspectors found this tough customer in a can of meat that had been sterilized with radiation but spoiled anyway.

Feisty D. radiodurans has the amazing ability to repair radiation damage to its DNA, usually within 24 hours. It keeps five stacked copies of its genome and protects itself by forming a tough outer layer of fatty lipid particles that can survive both the vacuum of space and punishing ultraviolet radiation. The microbe renders poisonous solvents and heavy metals harmless, while shrugging off intense radiation. The Department of Energy is using Conan to help clean up 3,000 polluted Superfund sites around the country.

Microbial Godzilla

Last, consider a creature that's like Godzilla compared to a normal extremophile. The remarkable tardigrade is no bigger than the dot above this *i*, yet it occupies a major branch in the tree of life. Often called "water bears," tardigrades have five body segments, four pairs of clawed legs, a single gonad, a multilobed brain, digestive and nervous systems, and separate sexes. Researchers have identified more than 750 distinct species.

Only a mother could love this intimidating arthropod, but their amazing adaptability deserves our respect. Tardigrades live in all climate zones. They handle temperatures from –328° F to 300° F (–200°C to 150°C). Pressures from vacuum to 1,000 atmospheres don't trouble them. And move over Conan, water bears can absorb a thousand times the radiation that would kill you or me.

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Water bears survive adversity by going into cryptobiosis, a truly deathlike state where metabolism plunges to 0.01 percent of its normal rate, or is undetectable. The organism's water content falls to 1 percent of normal. It forms a hard, waxy exterior called a tun, which renders it impervious to the elements. Lightweight, desicated tuns disperse on the wind and hitchhike on animals for long distances.

Alien extremists

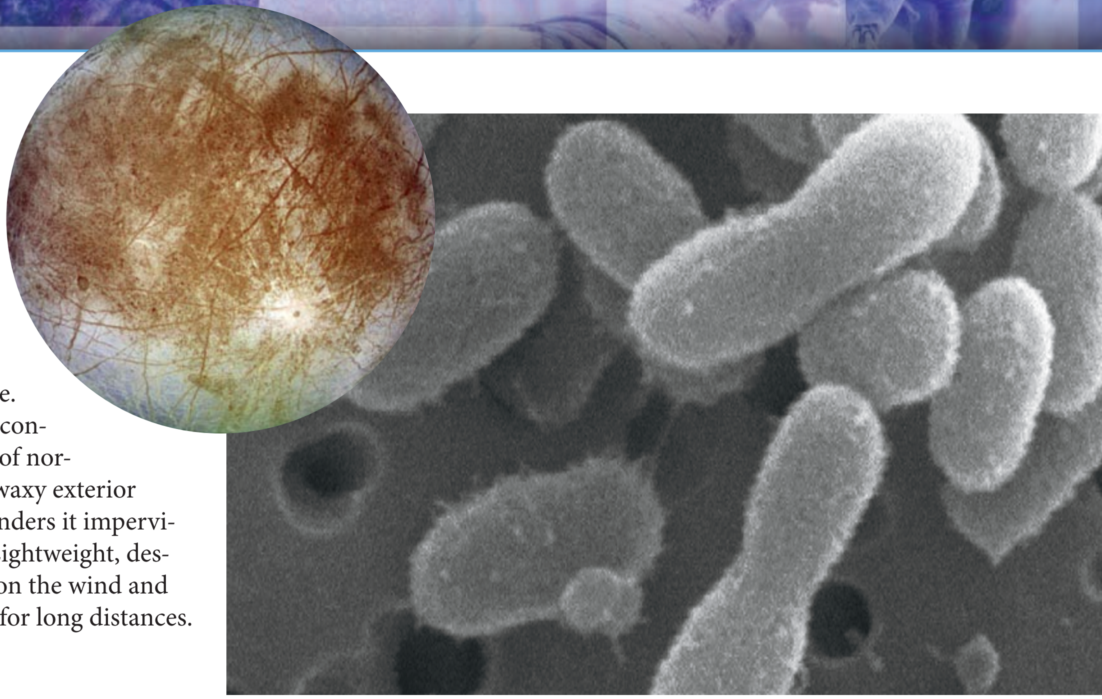
Earth must shape our expectations for finding biology elsewhere in the universe. Extremophiles challenge fundamental assumptions about what life is and what normal is.

The term extremophile is anthropocentric. Their environments seem extreme only to us. To an extremophile, they're normal. The range of adaptation of terrestrial life makes it more plausible that microbial life could exist in the martian permafrost, or in the frigid oceans of Europa, or in a half dozen other harsh and exotic environments in the outer solar system. Microbes might have hitchhiked on meteoritic debris between planets and moons. Extremophiles may even give us tips for our own travel in space, because cryptobiosis (suspended animation) is likely to be a requirement if we're ever to travel to the stars.

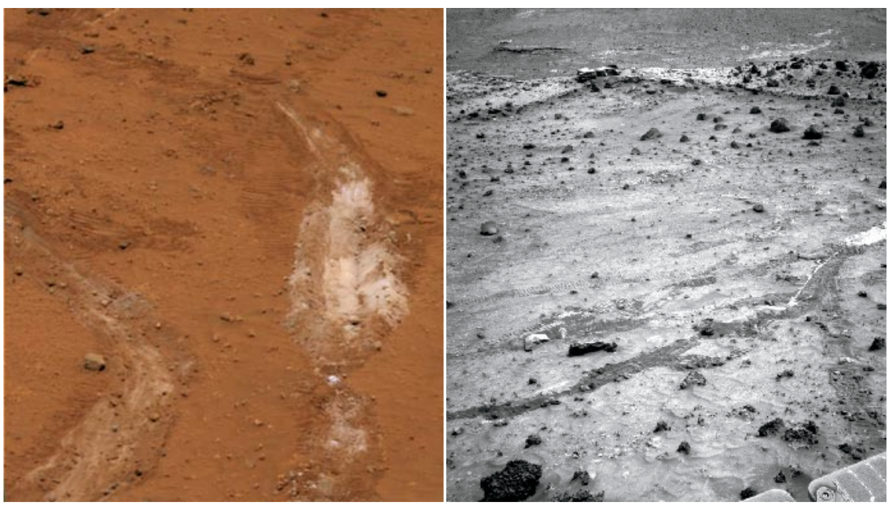
At the very least, extremophiles expand the definition of a star's habitable zone far beyond the slender range of distances at which liquid water can exist on a planet's surface. Extremophiles show that life on Earth is like a liquid that has filled the full "shape" of the environmental conditions. On planets beyond the solar system, we have every reason to believe that microbial life will adapt to local conditions and so may be weirder than anything we've seen on Earth.

Heat is available in the crust of any large planet or any moon gravitationally flexed by the planet it orbits. If life can thrive under a planet's crust or deep in its oceans, it may not need an atmosphere. If life can use hydrogen as a nutrient and get its energy from infrared radiation, it may be happy with any kind of host star — or may not need a star at all!

Across the cosmos, planets and moons covered by a web of extremophiles may be the norm. It's hard to feel kinship with Bacillus infernus, but the fecundity of the universe and the prospect of microbial life on millions of planets beyond the solar system are thrilling developments in astronomy.



The microorganism Chryseobacterium greenlandensis revived itself after lying dormant for 120,000 years in glacial ice at a depth of nearly 2 miles (3.2 kilometers). The existence of such a cold-hardened bacterium on Earth raises hopes of finding life in the solar system's frigid frontiers. One place that may harbor extraterrestrial extremophiles is the liquid ocean beneath the icy crust of Jupiter's moon Europa (inset). Jennifer Loveland-Curtze (PSU); Inset: NASA/JPL/DLR



Skid marks from the Mars Exploration Rover Spirit exposed a patch of bright-toned sand rich in the mineral silica. The marks lie within a larger area, called Home Plate (right), that may be the remnant of a volcanic hydrothermal system or volcanic vent. Such environments could have hosted colonies of martian extremophile bacteria. NASA/JPL/Cornell

Learn more about extremophiles on Earth at www.Astronomy.com/toc.