What is Astrobiology?

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Astrobiology is the scientific study of the origin, evolution, distribution, and future of life in the universe. The study of astrobiology brings together researchers from historically separate scientific fields such as microbiology, ecology, astronomy, geology, paleontology, and chemistry and encourages them to work together to answer the most fundamental questions science can pose: What is life? How did we get here? Are we alone in the universe? How can we tell if we are?

These questions have been asked for generations, but it is only recently that we have had the technology and the knowledge to address them from a scientific perspective. Understanding the answers requires that researchers develop a larger perspective than is possible within any one field of science. Astrobiology is a collaborative effort, transcending traditional scientific discipline boundaries.

Researchers begin by studying life on Earth, the only place in the universe where we know life exists. How did life begin here? How has it responded to changes in the environment? How has it changed the environment? What conditions does earthly life need to exist? The scientists of the NASA Astrobiology Institute, among others, seek to answer these questions and many more.

The next step is to look beyond Earth to the possibilities of life elsewhere. Most of life on the Earth is microbial, and it's likely that microorganisms will be the type of life we will find elsewhere in the universe. Astrobiology researchers try to figure out how to search for microbes and other life on the planets and moons in our Solar System and on Earth-like planets orbiting other stars. How do you detect evidence of biology when you can't hold a soil sample in your hand? Does life leave its mark on a planet so that we can detect its presence remotely? Is life common? Or is our life-filled Earth rare and unique?

Life and Water

Astrobiologists also struggle with the question: what exactly does it mean to be alive? Life as we know it here on Earth exchanges energy and materials with the environment. Lifeforms grow, develop, produce waste products, and reproduce, storing genetic information in DNA and RNA and passing it from one generation to the next. Life evolves, adapting to changes in the environment and changing the environment in return.
The basic unit of living things is the cell. Life is based on the chemistry of carbon and requires liquid water.

The “liquid” part is important. It's very hard to transport important substances, like nutrients or metabolites, from one place to another within a solid, and it's hard to control that transport in a gas. Liquids can do it well.

Water has many qualities that make it an ideal medium for the cellular biochemical reactions necessary for life. The chemical properties of water molecules help the other molecules of life, such as DNA, proteins (structural building blocks of cellular architecture and enzymes that speed up chemical reactions), and sugars (such as glucose, a common sugar used for energy), orient themselves in the proper three-dimensional shapes needed to carry out their functions in the cell. In order to maintain osmotic balance (and avoid drying out or swelling up), cells also need dissolved salts such as calcium and potassium. Water has wonderful capabilities to dissolve the nutrients and salts on which life depends, and the ability to move these molecules into and out of cells as it flows.

Water is the only chemical compound that is found naturally on Earth in all three physical states – as a gas, a liquid, and a solid. This property allows water to cycle through evaporation, condensation, and precipitation, between reservoirs in the oceans, on land, and in the air. Indeed, water is one of the few substances that can be liquid at the temperatures and pressures typical of the Earth's surface (mercury and liquid ammonia are the others). Water will remain liquid over an extremely large range of temperatures, freezing at 0oC (32oF) and boiling at 100oC (212oF). Adding salt will lower the freezing temperature, and adding pressure can raise the boiling point, increasing the range even more. Plus, it takes a lot of energy to raise the temperature of water a few degrees. All of which means that temperatures on Earth can undergo rather large variations before the liquid water freezes or boils away.

Some microbial and all multicellular life on Earth depends on the water molecule for survival in another, fascinating way. Many microorganisms and plants carry out photosynthesis, the biochemical process of creating sugars and atmospheric oxygen O2 from CO2 in the air and light energy from the Sun. Those same microorganisms and plants can then consume the sugars they create, converting them to usable energy needed for growth and reproduction. Many other organisms, such as animals (including humans), later consume the plants as food. The reactions of photosynthesis use the light from the Sun and liquid water to remodel CO2 from the atmosphere, forming sugars and breathable oxygen.

Life in Extreme Environments

On Earth, life is found anywhere liquid water is present. Only in the past few decades have scientists realized that "anywhere" includes such extreme environments as ice covered Antarctic lakes, hydrothermal vents on the ocean floor, and porous cracks in deep subsurface rocks. The organisms that live in these harsh conditions are called extremophiles. They survive and sometimes thrive in environments once thought too hot, too cold, too salty, too acidic, too high pressure, too dry, or with too much radiation for life to exist.

For example, scientists have long known that microbial mats (large colonies of microbes) are responsible for the beautiful colors observed in Yellowstone National Park's many hot springs. The water in these springs tops 90oC (188oF), much too hot to touch. Some hot springs are also extremely acidic, with pH levels in a few cases similar to that of stomach acid. Yet life thrives in and around them.

In 1977, scientists were stunned to discover abundant life clustered around hydrothermal vents on the ocean floor thousands of feet below its surface. The vents form where the Earth's crustal plates crack and spread apart. Molten rock, or magma, wells up along these cracks, forming long undersea mountain ranges known as mid-ocean ridges. Seawater seeps into the rock at the cracks, is heated, and shoots back upward through vents nearby, enriched with minerals dissolved from the rocks along the way.

Scientists thought life would be impossible in the extremely hot temperatures (113- 120oC, 235-248oF), oppressively high pressures (thousands of pounds per square inch), complete darkness, and toxic chemical brew typical near these ocean-floor vents. But the high pressure keeps the hot water from leaving the liquid state and becoming a gas. In place of sunlight, microbes living there use chemical reactions involving hydrogen sulfide, common in the enriched seawater pouring out of the vent, to generate energy. Other creatures survive by eating the microbes, or each other. Should the flow of hot, enriched water slow to a trickle for any reason, the creatures around the vent would soon die.

Lifeforms discovered at hydrothermal vents include many species of microbes, mussels, clams, shrimp, and giant tubeworms that can reach ten feet in length. The tubeworms have no stomachs or mouths. They depend on symbiotic bacteria in their guts for their nutrition, a relationship that benefits both the worm and the bacteria. Hemoglobin in the worms' red tips grabs hydrogen sulfide from the water around the vent and transports it to the bacteria living inside the worm. Using this hydrogen sulfide as an energy source, the bacteria in turn convert carbon dioxide dissolved in the water into carbon compounds that nourish the worm.

Researchers have also found bacteria in small pockets of liquid water embedded twelve feet deep in "solid" lake ice in the McMurdo Dry Valleys of Antarctica. These valleys are among the coldest, driest places on Earth, with average temperatures of -20oC (-4oF) and less than 10 centimeters (four inches) of precipitation a year. Small grains of dirt within the ice absorb sunlight to melt small amounts of the ice surrounding them, providing the liquid water needed to support life. The dirt also provides chemical nutrients for the bacteria that photosynthesize, grow, and reproduce in the liquid water pockets during the long Antarctic summer days.

The Rio Tinto in southwestern Spain is another interesting environment for life. The river has a deep red color, like red wine, because of iron dissolved in the water. It is highly acidic, with a pH of 2.0 in most of the river. The high acidity results from chemical reactions between the water and iron and sulfur minerals in the rocks around the river. Microbes living in the water also use the iron and sulfur minerals for chemical reactions that generate energy.

Metabolic products from these reactions contribute to the low pH of the river. Numerous algae and fungi also thrive there.

Scientists have discovered bacteria living in groundwater 5 kilometers below the surface in deep gold mines of the Witwatersrand Basin in South Africa. These thermophilic (heat-loving) bacteria thrive in cavities and cracks in rocks, living at temperatures that approach 80oC (176oF). Both bacteria and archaea have been found in the deep subsurface. They have diverse metabolisms, including sulfate reduction (sulfate is consumed and hydrogen sulfide is produced) and methanogenesis (acetate or carbon dioxide is consumed and methane is produced). The mass of all the microbes that live underground could approach or exceed the biomass of life on the surface of Earth. Scientists are also investigating life in and below the permafrost regions of Canada; these psychrophiles (cold-loving organisms) live at cold temperatures around 0oC (32oF). Looking for subsurface life in permafrost regions will help scientists develop tools to search for life in the subsurface of Mars.

“Extreme” vs. “Normal”

To extremophiles, the conditions in which they live are “normal” and "common." To them, the conditions we traditionally associate with life (moderate temperatures, sea level pressures, plenty of sunlight, an oxygen-rich atmosphere) are “extreme” and deadly. “Normal” and “extreme” are relative terms.

Conditions that we think of as “extreme” on Earth may be similar to what is “common” elsewhere in the Solar System. Understanding how life survives in earthly extreme environments can help scientists better understand how life could exist on other planets and moons.

One thing extremophiles have in common with the rest of us is that they, too, require liquid water to survive. Consequently, when scientists think about non-earthly places where life may exist, they look for sites where liquid water either is now or was once at some time in the past.

Life on Mars?

Mars today is a frozen, dry world. Its predominantly carbon dioxide atmosphere is too thin to support liquid water on its surface, and its surface temperatures are too cold, averaging -65oC (-85oF). Yet its surface is covered with winding channels that resemble ancient riverbeds, and there is water ice frozen in the planet’s polar ice caps and subsurface permafrost. Enormous extinct volcanoes indicate Mars was once tectonically active, even though its core is now too cold to support volcanic activity. These geological observations, combined with data from the Mars Exploration Rovers – Spirit and Opportunity – (http://marsrovers.jpl.nasa.gov/home/) indicate Mars once may have had a thicker, warmer atmosphere and liquid water standing and flowing on its surface. Could life have emerged at that time? Did it find a way to adapt, evolve, and survive the shift from moderate to extreme conditions? The frozen deserts of Antarctica resemble the Mars of today. If life can persist deep in the ice and in Earth’s subsurface, perhaps it survives in the permafrost or polar ice caps of Mars.

An Ocean on Europa?

Europa, a moon of Jupiter which is slightly smaller than Earth’s Moon, is one of the smoothest objects in the Solar System. Most scientists think there is a liquid water ocean between 50 and 100 kilometers deep surrounding Europa’s rocky interior, and that the ocean is in turn covered by a layer of water ice a few kilometers thick.

Few craters from meteorite impacts mar this moon’s icy crust, indicating Europa’s surface may be only a few million years old (on old surfaces, meteorite strikes accumulate and many craters are seen or can be counted). Cracks and streaks crisscross Europa’s surface. Scientists think water seeps up through cracks in the ice caused by the gravitational twisting of the ice sheet, creating the streaks observed on the surface.

Europa is deformed into a slightly oval shape by Jupiter’s strong gravitational pull, in much the same way the Moon’s smaller gravitational pull causes the oceans to bulge in tides on the Earth. But Europa also feels a gravitational pull from each of Jupiter’s other large moons, and the combination of all these conflicting tugs causes Europa to twist and flex as it orbits Jupiter. This tidal flexing has heated Europa’s interior, and may explain the ocean under the ice.

A curious analog to Europa’s ice-covered ocean can be found in Antarctica. In 1996, scientists discovered evidence of a lake of liquid water deep underneath the ice at Russia’s Vostok Station ~1,000 kilometers (~600 miles) from the South Pole. Dubbed Lake Vostok, the liquid water sits under ~3,710 meters (~12,000 feet) of ice and may have been isolated for 500,000 to a million years. Lake Vostok, about the size of Lake Ontario, is thought to be about 484 meters (1,588 feet) deep, with ~50 meters (~160 feet) of sediment at its bottom. No one knows if there is any kind of life in Lake Vostok. So far, scientists have not drilled into the lake’s water, because organisms carried in the drilling equipment can contaminate the lake. Contamination by earthly organisms is a concern for researchers who want to look for evidence of life on Mars and in Europa’s ocean, too. Techniques for drilling without contamination will prove invaluable when landers and subsurface probes are sent to explore Europa and Mars.

Titan’s thick atmosphere

Titan, Saturn's biggest moon, is the only moon in the Solar System with a thick atmosphere. Methane clouds float close to the surface. A thick smog of organic molecules, ~300 kilometers (~190 miles) above the ground, and a thin haze high in the outer atmosphere complete the picture. These clouds and haze keep nearly all sunlight from reaching Titan’s surface, which remains at -180oC (-292oF).

The Cassini-Huygens spacecraft, a joint effort of NASA, the European Space Agency, and the Italian Space Agency, inserted into Saturn’s orbit on June 30th, 2004. The Huygens probe, released from the Cassini spacecraft on December 24th, entered Titan's atmosphere on January 14th, 2005, and landed safely on the ground two hours and 32 minutes later. The probe revealed striking images of drainage channels leading toward an apparent shoreline, as well as small, smooth, rounded rocks not unlike river rocks on Earth. Because the frigid surface is too cold for liquid water, scientists have speculated that the fluid responsible for carving the channels could be liquid methane. The “penetrometer” on the bottom of the probe sampled the surface and found it has the consistency of wet sand or clay, covered by a thin crust.

Cassini remains in orbit, collecting information on Titan during its periodic fly-bys. Images have depicted a dark feature on Titan’s surface that resembles Earth’s Lake Ontario in size, with smooth, shore-like boundaries, but more likely filled with liquid hydrocarbons instead of water. Cassini continues to “lift Titan’s veil,” by revealing a land of mountains and river channels near Titan's equator in April, 2006. Cassini's radar will continue to illuminate this mysterious and compelling moon, aspects of which may resemble conditions on Earth before life began.

Impact of extremophiles

The extreme environments of Mars, Europa, and Titan may or may not harbor life. We do not yet know. Fortunately, scientists can use earthly extreme environments to test equipment and techniques they may someday use to search for life on these and other planets and moons. For example, scientists have drilled into the rocks under Spain’s Rio Tinto, looking for extremophiles. Subsurface conditions there may resemble those on Mars, where underground liquid water could exist amid rocks rich in sulfur and iron. Experience with the drilling machines used at Rio Tinto will give important insight into the design of drilling machines that could be sent to Mars in the future.

Earthly extremophiles have forever changed our view of life and the conditions life needs to survive. Their existence has proven that life can exist in a broad range of environments. They have allowed scientists to expand their ideas of where to look for life. It is not enough to know only about biology when looking for life. Life leaves clues that biologists can detect – but some clues will go unnoticed or unappreciated without the collaboration of chemists, geologists, ecologists, and others. Astrobiology provides the umbrella under which scientists trained in these and other fields collaborate to understand life here on Earth as well as the possibilities of life elsewhere in the universe.