

# LIFE'S PRIMORDIAL BREW

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If a space probe were to land one day on Saturn's moon Enceladus or another distant world, would humanity recognize life there if it existed? The building blocks of life, amino acids and nucleobases, are certainly abundant in space. But what exact ingredients and environmental conditions are needed for life to emerge? Researchers at the Max Planck Society hope to find the answer by looking back and asking: how did living biology emerge from lifeless chemistry on Earth in the first place?

The quality of "being alive" seems obvious: a bacterium is alive, a stone is not. But as soon as specialists try to formulate a universal definition, biology, chemistry, cosmology, and philoso-

phy begin to jostle for position. One possible compromise is to require three core properties.

First, life must have a metabolism. A living cell, for instance, takes in energy and uses it to construct complex molecules. Second, a living entity must be distinguishable from its surroundings. Molecules drifting around do not constitute life, however complex they may be. Only when they have a membrane that holds them together and separates inside from outside does a system capable of life emerge. Third, the system must pass information on to its offspring during reproduction, whether through DNA,

RNA, or some entirely different mechanism. Otherwise, each generation starts from scratch.

These three criteria sound elegant, but they immediately raise new questions. Do all of them always have to be met? Viruses have genetic information but no metabolism – yet aren't they alive in some sense? And what, exactly, counts as a metabolism? Could a hypothetical life form on a distant moon not draw on energy in ways entirely unlike life on Earth? "I look at life as it exists here on Earth, because it is the only life we know," says Martina Preiner. The chemist leads the Geochemical Proto-Enzymes →

# KNOWLEDGE FROM

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*Habemus vitam!* At least that is what researchers believe: life, or at least the first metabolic reactions, may have formed at hydrothermal vents. At the Iguanas hydrothermal field near the Galápagos Islands, water heated to hundreds of degrees Celsius emerges from the Earth's crust, carrying dissolved minerals that account for the black color of the emissions and deposit along the vent chimneys.



working group at the Max Planck Institute for Terrestrial Microbiology in Marburg and investigates how life on Earth may have originated.

the distant past: 4 billion years ago, in fact. Researchers are approaching that distant past from two directions.

carbon dioxide as a source of carbon, probably hydrogen to provide energy and electrons, and probably transition metals such as iron, cobalt, and nickel.” Single-celled organisms with exactly this metabolism still exist today, in marine sediments and the stomachs of cows.

From the moment the first functioning microbe existed, the rest of the story becomes easier to follow. It is still not entirely clear how single-celled organisms without nuclei gave rise to ones with nuclei, or how multicellular life then evolved from them. But “science has many ideas and pieces of evidence,” as Preiner puts it. What came before that, though? How did that first functioning microbe arise? Here the trail disappears into the mists of

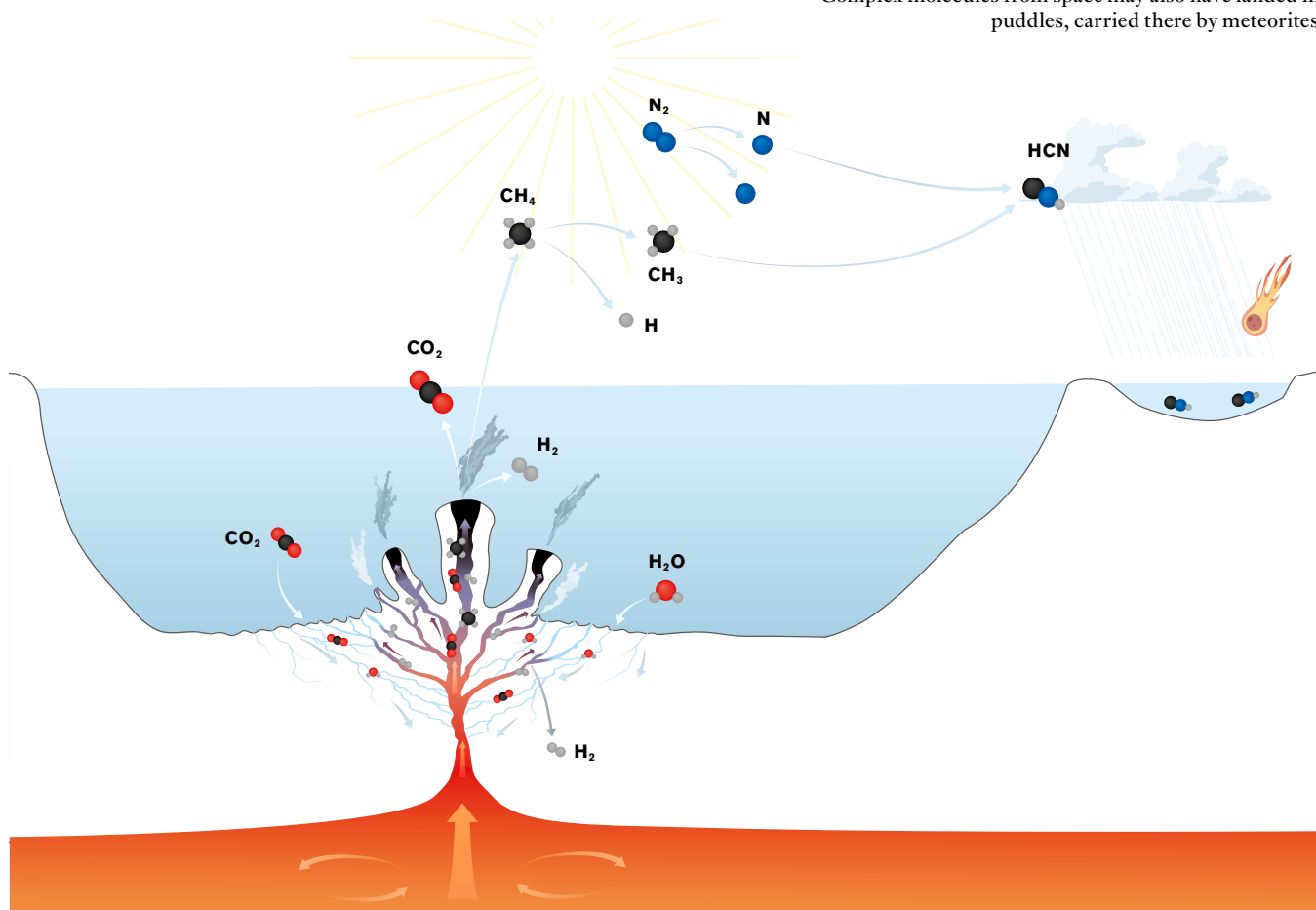
## Meet Luca!

The first approach is genetics: starting from single-celled organisms alive today, researchers reconstruct the tree of life. At its root sits the hypothetical ancestor of all life on Earth – the Last Universal Common Ancestor, known as Luca. It is a theoretical construct, the bare minimum a functioning cell must once have required. “What did Luca live on?” asks Preiner. “Probably

The second approach to getting closer to Luca is chemistry: starting with simple chemical compounds, researchers use calculations and experiments to work out how the primordial cell could have emerged from them. “We do not know exactly what Luca looked like or how it could have arisen,” says

Chemistry of the young Earth: hydrogen ( $H_2$ ), carbon dioxide ( $CO_2$ ), and methane ( $CH_4$ ) escape from hydrothermal vents on the ocean floor.  $H_2$  forms through rock alteration, known as serpentinization, where magma meets seawater penetrating the crust and carrying dissolved atmospheric  $CO_2$  and  $N_2$ . In the atmosphere,  $CO_2$  then reacts with  $H_2$  to form  $CH_4$ . The sun’s UV radiation splits  $CH_4$  and  $N_2$ , and rainwater fills ponds with newly formed HCN molecules.

Organic material thus forms at vents and in puddles. Complex molecules from space may also have landed in puddles, carried there by meteorites.



Preiner. Two schools of thought dominate the debate: the RNA-first hypothesis and the metabolism-first hypothesis.

The RNA-first theory assumes that life began with RNA molecules that carried information. RNA can reproduce itself and act as a catalyst, serving both as genetic material and as a driver of metabolic reactions. The idea is that once such a molecule existed, everything we now think of as metabolism followed almost automatically. Chemists have since discovered pathways describing how RNA building blocks formed on early Earth before life existed. Even so, many questions remain unresolved, including how the complex metabolism found in living organisms today emerged from RNA.

“I cannot imagine how something as complex as RNA could give rise to the smaller-scale components of a metabolism,” says Preiner. She researches the metabolism-first theory. This hypothesis holds that there were small chemical cycles – sequences of chemical reactions that run entirely on their own using whatever ingredients happen to be available. They are pure geochemistry. Genetics may have emerged from these chemical cycles. “This view seems plausible to me because it proceeds in smaller steps: simple chemistry gives rise to chemical cycles, which gradually become denser and more complex.” But science can’t say whether one approach is superior to the other. “The only evidence we have for the origin of life is life as it exists today,” Preiner says. It is entirely possible that both mechanisms played a role.

The chemist is interested in a specific detail of the metabolism-first theory. A cell separated from its environment needs an exchange between inside and outside in order to draw energy from its surroundings. Lipid membranes are among the oldest structures in life that make this process possible. “But Luca did not yet have those at its disposal. So how did the first cell draw energy from its surroundings?” Preiner asks. The answer may lie in rock pores: tiny cavities in

early iron-rich silicate rock found at hydrothermal vents, which are chimneys on the ocean floor from which hot water escapes. “Luca’s basic metabolic reactions could occur there spontaneously,” Preiner says. One explanation would be this: the porous rock acts as a kind of crucible for such

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## SUMMARY

Martina Preiner of the Max Planck Institute for Terrestrial Microbiology and Klaus Paschek of the Max Planck Institute for Astronomy are investigating two hypotheses that could explain how life arose on the early Earth.

Preiner studies simple metabolic cycles in the environment around hydrothermal vents on the ocean floor. Paschek examines the early formation of RNA molecules in moist surface ponds. Meteorite impacts in such puddles may have provided a chemical boost.

Both processes were probably at work at the time. Although no life beyond Earth has yet been detected, the prerequisites – such as liquid water – may also exist on other planets and moons. Saturn’s moon Enceladus, for example, has already yielded early signs.

a metabolism. Water reacts with the iron present in the rock to produce hydrogen gas (H<sub>2</sub>). Minerals found within the porous rock – among them iron ores and nickel-iron compounds – accelerate the reaction of H<sub>2</sub> with CO<sub>2</sub>, just as in Luca’s metabolism. Similar ingredients can still be found in modern enzymes today.

In laboratory experiments, Preiner and other researchers have also observed these reactions between CO<sub>2</sub> and H<sub>2</sub>

in water on mineral surfaces. Overnight, they produced the same organic molecules that form the backbone of LUCA’s metabolism: formic acid, acetic acid, and pyruvate. With ammonia, and again with the help of minerals, these compounds can go on to form amino acids, the building blocks of proteins. From there, it is only a short step to the first nucleobases that make up genetic material.

The rock pores offer another advantage: they create an environment that is moist but not wet. “Water is indispensable for life, but when life is forming, water also gets in the way,” says Preiner. Too much water washes molecules away before they can combine. Around hydrothermal vents, however, much of the water is chemically bound within the rock. The pores, just a few nanometers in size, are moist enough for chemistry to occur but dry enough not to tear fragile molecules apart. “This kind of setting, with alternating wet and dry conditions, allows different chemical reactions to occur one after another and may therefore have been a key factor in the origin of life.”

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## It Rained Hydrogen Cyanide

While Preiner investigates how early biochemical compounds develop in porous rock, Klaus Paschek at the Max Planck Institute for Astronomy is exploring a different possibility in the laboratory and on the computer: life from exhaust gases. The early Earth was covered by a vast ocean, its seafloor alive with hydrothermal vents belching hot, mineral-rich water, hydrogen, and methane. The gases rose into the atmosphere, where they encountered the UV radiation of the young sun. “UV radiation was more energetic back then than it is today,” says Paschek. “That set photochemical reactions in motion and turned those gases into our favorite building block: HCN, or hydrogen cyanide. Rain then washed the hydrogen cyanide onto the land, into small pools and puddles, where water repeatedly evaporated, and more →

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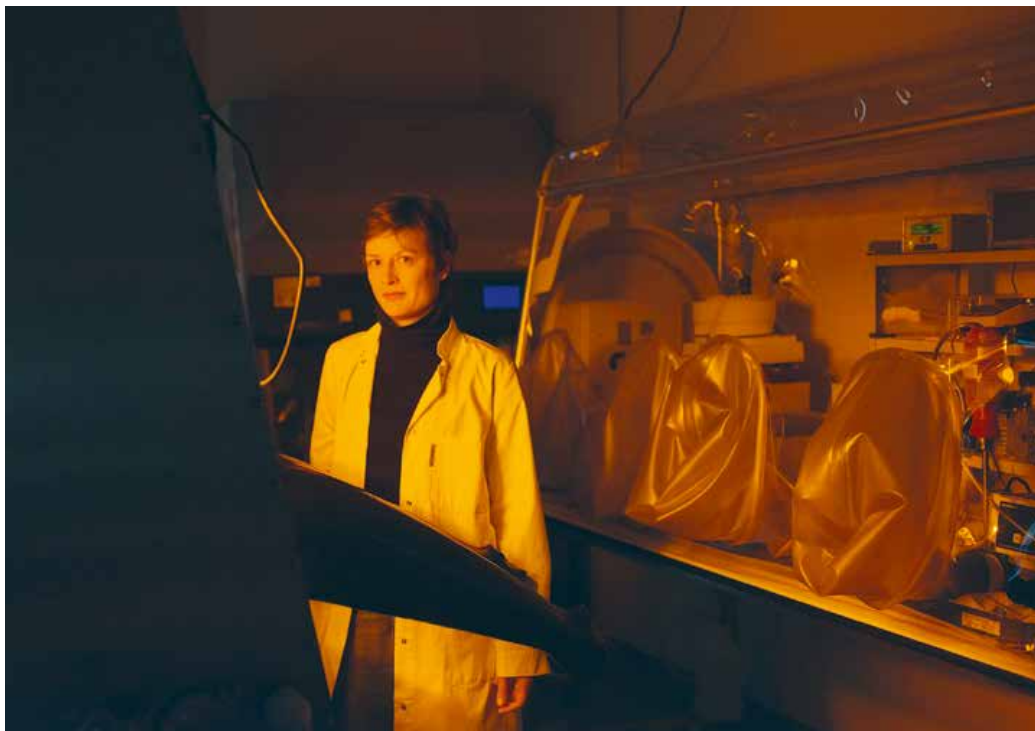


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rain repeatedly replenished it.” The wet-dry cycles in these “Darwinian puddles” resemble the cycles that may also have occurred in the rock around hydrothermal vents. Warm, chemically rich puddles of this kind offer an ideal environment for simple chemical ingredients to combine into something new and complex. So, whether life began in deep-sea rock or in surface puddles, the two hypothesized birthplaces of life appear to have much in common.

## A Cosmic Boost for Life

“Perhaps the puddles also got a boost from space,” says Paschek. “A fragment of an asteroid may have crashed into a Darwinian puddle and brought along some of life’s building blocks.” Asteroids are not simply dead lumps

of rock: many were heated from within in the early solar system by radioactive decay, and some even contained liquid water. According to the hypothesis, simple molecules in these warm, water-rich rocks, including hydrogen cyanide (HCN) and ammonia, gave rise to more complex organic compounds, among them precursors of RNA building blocks and sugars. For Preiner, the fact that biomolecules also form in space shows just how naturally such molecules come together.

Another share of these organic compounds probably formed much earlier in the protoplanetary disk where the sun and planets took shape: dust grains coated with water and methanol ice were irradiated by UV light and chemically altered. According to this scenario, basic chemical ingredients formed there and later turned up in asteroids too. If a meteorite broke

off such an asteroid and fell into a puddle on the early Earth, it could have brought with it a cocktail of chemicals: building blocks of DNA and RNA, simple sugars, and more, from which the first biological molecules formed. “Our theory is unconventional,” Paschek admits. In a warm puddle, terrestrial and cosmic chemistry may then have come together and shaped the first faint stirrings of life from inanimate matter.

“In principle, a molecule like HCN can be used to cook up almost everything a cell needs,” says Paschek, and both outer space and the early Earth could supply the necessary ingredients, whether in asteroids, hydrothermal vents, or warm ponds. Earth’s atmospheric chemistry had one decisive advantage, however: “Meteorite impacts were isolated events, brief chemical jolts. Volcanoes, by contrast, continuously pumped gases into the



*Left:* Martina Preiner stands in front of glove boxes in the laboratory of the Max Planck Institute for Terrestrial Microbiology. These devices help to simulate the anaerobic conditions of the early Earth.

*Right:* at the Max Planck Institute for Astronomy, Klaus Paschek (red T-shirt) shields himself from a UV laser that excites artificially produced molecules of the kind that could form in space. Michael Hermann (center) and Tushar Suhasaria (front) are preparing to analyze those molecules.

atmosphere, UV radiation set reactions in motion, and rainstorms carried the products down into puddles.” Geochemistry thus provided a steady supply of ingredients. That made it less of a problem if a handful of early life forms fell victim to hostile environmental conditions such as intense UV radiation. Preiner believes, in any case, that all the earliest building blocks must have originated on Earth: “Even if amino acids or nucleobases reached us from space on asteroids, life on Earth would still have had to find a way from the very beginning to forge this material itself, without relying on outside supplies. Life is the interplay of building blocks within metabolism, not the sum of the molecules themselves.”

Could a meteorite possibly crash into a warm puddle on another planet or moon, thus giving rise to life? At minimum, liquid water would be required

and with it an atmosphere. On Earth, the pressure of the atmospheric layer above the surface keeps water liquid. Solar radiation causes parts of the ocean to evaporate, while the exchange of air between regions of differing atmospheric pressure produces winds that carry water vapor away before it condenses again as rain. Wet-dry cycles of this kind can therefore occur only on Earth-like planets.

So far, no telescope has found liquid water on rocky planets the size of Earth. Either Earth is truly exceptional, or researchers have simply had bad luck with the planets studied so far. Super-Earths – rocky planets more massive than Earth – are easier to detect on account of their greater mass. Many of them are likely to be more geologically active and even to have atmospheres. There are at least indications of water vapor in the atmospheres of such planets. Water vapor would also be easier to detect than liquid water, but researchers are not yet certain. The Extremely Large Telescope, which within a few years will become Earth’s largest eye on the universe and will study exoplanet atmospheres, could bring greater clarity. If water exists there, the processes Paschek is investigating could be happening.

Liquid water and trace elements associated with life are fairly reliably found in less hospitable places too, such as beneath the thick ice shell of Saturn’s moon Enceladus, where the Cassini

spacecraft detected organic molecules in the water vapor and erupting ice plumes. These molecules could have arrived via protoplanetary dust grains or asteroid fragments. There also appear to be hydrothermal vents on the floor of an ocean inside Enceladus, piercing the moon’s continuous ice shell. In that environment, water, rock, and energy come together, providing the foundation for the kind of life Preiner studies.

“I believe simple microbes probably exist elsewhere as well,” Paschek says. “Complex life forms probably do not. After all, it took 4.5 billion years on Earth for *Homo sapiens* to emerge.” Preiner also considers extraterrestrial life possible: “I am optimistic that we could find precursors of life on Mars.”

Biology versus chemistry, RNA versus metabolism, hydrothermal vents versus Darwinian puddles: Paschek sees no clear front-runner. “The origin of life is so improbable that nature probably exploited every available advantage and used everything it could get its hands on.” Perhaps there is no single primordial soup, but several. Perhaps different precursors of life developed alongside one another simultaneously – multiple Lucas, of which only one lineage survived? Humanity, then, may not be unique, but simply one of many outcomes of the same cosmic experiments, while somewhere else a new metabolism is at work on its own version of this accidental history.

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