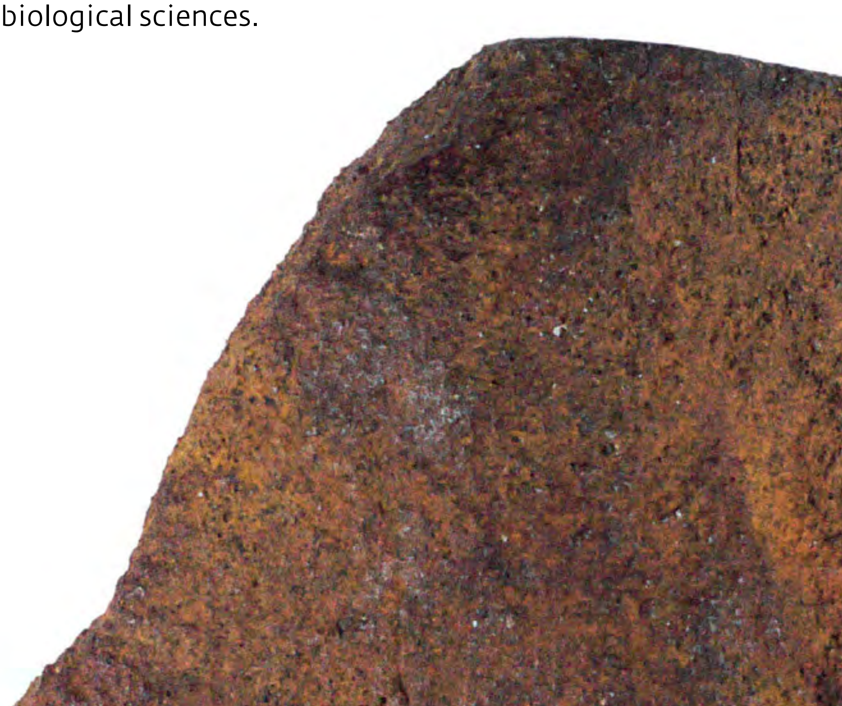
Building blocks that **fall from the sky**

How did life on Earth begin? Scientists from the "Heidelberg Initiative for the Origin of Life" have set about answering this truly existential question. Indeed, they are going one step further and examining the conditions under which life can emerge. The initiative was founded by **Thomas Henning**, Director at the **Max Planck Institute for Astronomy** in Heidelberg, and brings together researchers from chemistry, physics and the geological and biological sciences.



TEXT **THOMAS BUEHRKE**

The great questions of our existence are the ones that fascinate us the most: how did the universe evolve, and how did Earth form and life begin? Does life exist anywhere else, or are we alone in the vastness of space? By approaching these puzzles from various angles, scientists can answer different aspects of this question. For a long time, there was a clear division of tasks: astrophysicists and geophysicists were responsible for studying the universe and Earth, biologists and chemists for studying life. However, recent developments are forcing researchers to break down this specialization and combine different disciplines. "That's what we're trying to do with the Heidelberg Initiative for the Origins of Life, which was founded three years ago," says Thomas Henning. HIFOL, as the initiative's name is abbreviated, not only incorporates researchers from different disciplines, but also cooperates closely with international institutions such as the McMaster University in Hamilton, Canada.

The initiative was triggered by the discovery of an ever greater number of rocky planets orbiting around stars other than the Sun. "We now know that terrestrial planets of this kind are more commonplace than the Jupiter-like gas giants we identified initially," says Henning. Accordingly, our Milky Way alone is home to billions of rocky planets, some of which presumably offer environmental conditions that favor the emergence of life as we know it. It is precisely this realization that broadens the scope of the Heidelberg Initiative: it

Precious cargo: meteorites may have brought key chemicals – such as the nucleobases adenine, guanine and uracil – to Earth, thereby providing the ingredients for the formation of RNA molecules.

Photo: DLR

Cosmic nurseries: stars and planets form in clouds of gas and dust. The image above shows three such areas: the Omega and Eagle Nebulae and the Sharpless 2-54 complex (from left). This process of formation not only gave rise to our solar system some 4.6 billion years ago, but also continues to take place at many locations in space. It is also responsible for producing the red dwarf star Trappist-1, which is located 40 light years from Earth, and the seven relatively Earth-like rocky planets that have been identified in its system so far (right).

must ask not only how life could have emerged on Earth but also, more generally, what conditions are needed for something like this to happen – including on extrasolar planets.

PRAISE AND CRITICISM FOR AN EXCELLENT STUDY

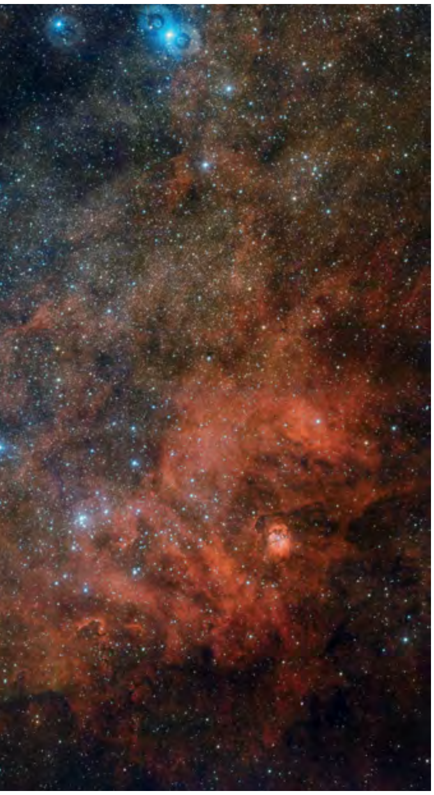
Late last year, Thomas Henning and his colleague Dmitry Semenov, as well as Ben Pearce and Ralph Pudritz from McMaster University, caused quite a stir with a publication in which they proposed a scenario for the emergence of life on Earth. “As well as recognition and praise, it also brought us some criticism,” says Henning.

The criticism came from the more traditional origins-of-life scientists, who challenged the study of the astronomers following the thought: what do astronomers understand about biomolecules – even if they have a deep knowledge of astrochemistry? The National Academy of Science took a different view, however, and awarded the publication the 2017 Cozzarelli Prize for its “outstanding scientific excellence and originality”. In fact, astronomers can indeed contribute to questions of what conditions potentially existed when the first molecules of life or their precursors were formed – and of how this came about.

As a starting point for the study, Henning and his colleagues applied the widely used “RNA world” hypothesis proposed some 30 years ago by Walter Gilbert, a Nobel Prize winner in Chemistry. This states that the first ever terrestrial life forms were based on ribonucleic acids (RNA). Structurally, RNA resembles DNA, the information carrier of life today: both are made up of four organic bases, including adenine, guanine and cytosine; however, RNA contains a base known as uracil instead of thymine. In addition, RNA is typically single-stranded – unlike the double-stranded structure of DNA.

Likewise, molecules of RNA can also communicate genetic information and perform catalytic functions. In most organisms, however, RNA serves as an information carrier in a subordinate role to DNA, only acting as a storage medium in viruses. Did the more complex DNA therefore evolve from simpler RNA molecules or related biopolymers?

Photo: ESO



In 2009, a chemical experiment by British researchers was considered a major breakthrough, for it showed that RNA building blocks can form if certain molecules are present and react with one another under very specific conditions. But where were the most favorable conditions present in nature?

For a long time, it has been suspected that life emerged at hydrothermal vents – so-called black and white smokers – on the deep seafloor. However, it is unclear whether the nitrogen needed for synthesis exists at a sufficient concentration in that environment. Moreover, the substances are diluted by a steady flow of water, which prevents complex chemical reactions from taking place.

“This is where we come into play,” says Thomas Henning. “We asked ourselves what other geochemical conditions might have been present to allow this RNA synthesis to take place.” The idea is that the most important building blocks came to Earth from space. Indeed, the nucleobases adenine, guanine and uracil, as well as amino acids, have been detected inside meteorites. These bases are formed from simple molecules of hydrogen cyanide, carbon monoxide and ammonia in the presence of water.

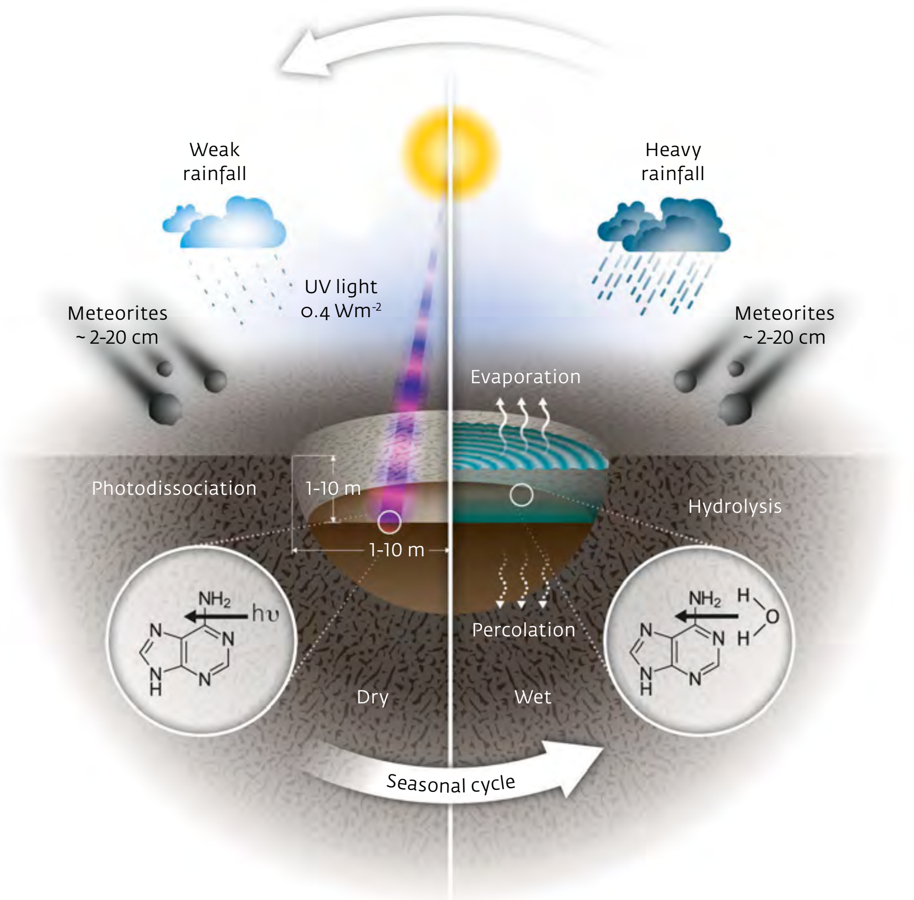
ZIRCON CRYSTALS INDICATE A SOLID CRUST

Meteorites have also been found to contain the mineral Schreibersite, which releases phosphorus capable of forming phosphorylated molecules in water – these too are required for RNA synthesis. Astronomical observations have shown that all of the necessary precursor materials to form RNA are present in the dust discs in which planets form, so they must also have been present in the solar nebula that gave birth to our solar system 4.6 billion years ago. But how and when did the organic building blocks arrive on Earth? And what did Earth look like at the time?

There are almost no remnants of the very early phase in which Earth cooled from a glowing ball into a rocky planet. Only the presence of tiny zircon crystals, which could be as much as 4.4 billion years old, suggests that Earth formed a solid crust at quite an early stage. At that time, Earth was exposed to a much heavier bombardment of meteorites than it is today, as is demonstrated by crater statistics for the Moon, which received the same onslaught. The cosmic projectiles presumably brought both water and organic molecules to our planet.

Just as little is known about the distribution of land and water in primeval times as it is about the temperature, for example, which is a crucial factor in chemical reactions. For this reason, the astronomers calculated models in which they varied key parameters of the developing crust over a wide range of values. Earth at the time undoubtedly had water reservoirs with a wide range of sizes, just as it does now. >

Photo: M. Kornmesser/ESO



The cradle of life: Dmitry Semenov (left) and Thomas Henning from the Max Planck Institute for Astronomy have outlined a scenario in which various reactions once occurred in small, warm pools. These reactions led to the formation of the first self-replicating RNA molecules. The diagram on the left shows the numerous influences that affected chemical compounds in these small bodies of water.

Graphic: McMaster University

Large lakes and seas were presumably unsuitable breeding sites for RNA, because the precursors must be present in concentrated form in order to react with one another. However, the model showed that small pools with a diameter and depth of just a few meters were ideal: they were large enough not to dry out too quickly, yet small enough to allow high nucleobase concentrations to accumulate rapidly.

At the same time, the biomolecules were at the mercy of destructive influences: in the water, they were endangered by electrolysis and, in the open, by the intensive UV radiation of the sun. Some 95 per cent of UV radiation is absorbed by a layer of water just one meter thick. The optimum scenario seems to be one where the pools experienced seasonal variations in fill level due to rainfall and drying out through evaporation and percolation: "The cycles in which shallow pools first dry out and then fill up with water again may have favored the formation of longer RNA chains," says Henning.

THE IDEAL RADIUS IS BETWEEN 40 AND 80 METERS

In the model simulations, the researchers also varied the impact rate and size distribution of the meteorites. If these are too small, they burn up completely in the atmosphere; if they are too large, they hit the ground with too much kinetic energy. "A radius of between 40 and 80 meters is the optimum size to allow the meteorites to deliver their molecular payload to the ground," explains Dmitry Semenov, an expert in chemical networks within protoplanetary discs and co-author of the study.

This range is two to four times the size of the meteorite that exploded over the Russian city of Chelyabinsk in February 2013. As that incident demonstrated in impressive fashion, meteorites of this order of magnitude do not make it to the ground unscathed – rather, they break up into many small fragments and fall to Earth over a large area. This means it is possible for tiny pieces, measuring just a few centimeters across, to have landed in the pools. Depending on their size, they would then have released the nucleobases over a period of several days to months. After that, the nucleotides – and the RNA molecules formed from them – would have to be synthesized within a few years.

The simulations show that meteorites could have transported a sufficient quantity of nucleobases, to small pools on Earth and thereby triggered the formation of RNA molecules in at least one such pool. The RNA world could have emerged within 200 to 300 million years from the point at which Earth's surface became habitable – that is, over four billion years ago.

“Based on what we know about planet formation and the chemistry of the solar system, we’ve proposed a consistent scenario for the origins of life on Earth,” says Semenov. “Now, the experimentalists need to work out how life could actually have emerged under these very specific early conditions.” In fact, the nucleobases are just the first step. Other necessary processes include, for example, the formation of complex RNA-like molecules, cell membranes and ultimately the DNA-protein world of today’s organisms.

It is impossible to talk about chemical experiments relating to the origins of life without mentioning the famous Miller-Urey experiment in the 1950s. Stanley Miller and Harold Clayton Urey placed simple chemical substances within a hypothetical early Earth atmosphere inside a reaction vessel. They then exposed them to electrical discharges in order to mimic the energy supplied by flashes of lightning. After some time, they were able to detect organic molecules, including amino acids, using a chromatograph.

Today, however, researchers assume that Earth’s primordial atmosphere had a different composition to that assumed by Miller and Urey, containing less methane and instead higher levels of hydrogen, carbon dioxide, nitrogen and water. In these conditions, it was probably more difficult to synthesize the necessary building blocks for RNA.

GENUINE METEORITE MATERIAL REACTING IN A REACTOR

The job of investigating how this could have been possible falls to Oliver Trapp, who carried out research at the University of Heidelberg before accepting a professorship at LMU Munich. In order to maintain his productive collaboration with the team in Heidelberg, he has become a Max Planck Fellow: the Max Planck Society supports him with research funding and finances part of his 16-person group.

“In our chemical experiments, we reproduce the conditions stipulated to us by the astrophysicists,” says Trapp. The researchers therefore take real meteorite material and place it in a reactor, where its reactions then produce numerous organic molecules that can be analyzed using fast chromatographic techniques. The results are surprising: the tiny meteorite particles on the nanometer scale act as catalysts for these reactions.

Interestingly, substances formed in the process then act as catalysts themselves, speeding up the production of the same or even other substances. The reaction enters a state of dynamic imbalance: only the substances that form catalytically the fastest are able to accumulate in large enough quantities. “A

Photo: Axel M. Quetz/MPI for Astronomy

Evolution in the lab: working with Harold Clayton Urey in the 1950s, Stanley Miller (pictured) succeeded in producing organic molecules in a reaction vessel – including amino acids. This famous experiment is today inspiring researchers to carry out further tests.

sort of chemical evolution takes place," says Oliver Trapp. "The aim is to see whether this chemical evolution leads to an RNA world." In these experiments, it has also become apparent that a kind of motor is needed to drive the reactions: the natural light/dark cycle of day and night. In other experiments, Trapp's group is studying fatty acids and the question of how cell membranes could have formed.

The analysis of chemical reactions in different conditions requires the use of high-throughput screening techniques, which allow Trapp's laboratory to run and analyze chemical processes in 64 minireactors, each with a capacity of just 1.5 milliliters. If certain conditions prove especially promising at this stage, they are then studied in greater detail in two-liter reactors. "We jokingly refer to this as our Urey-Miller 2.0," says Trapp.

SEARCHING FOR BIOMARKERS IN THE ATMOSPHERE

The reactions are very complex, and the researchers are only just beginning to address many of the questions. However, Oliver Trapp believes that the emergence of life is inevitable if the conditions are right. "I'm even convinced that the chemical structure of potential extraterrestrial life will closely resemble that of life on Earth."

This also raises the question of whether we will be able to detect the activity of life on another planet. The corresponding biomarkers are generally considered to be molecular oxygen, ozone and methane. However, it is important to bear in mind that the oxygen concentration on Earth did not reach its current value until approximately 300 million years ago. That is a relatively short time frame in terms of biological evolution.

In addition, detecting these substances on an exoplanet could be hampered by a problem that has been hitherto unknown – one that affects planets orbiting cool, low-luminosity stars known as "M dwarfs". The latest examples of such planets are Proxima Centauri b and Trappist-1d. In these systems, the habitable zone lies much closer to the star than is the case with our hotter Sun. A potentially inhabited planet will therefore presumably exhibit bound rotation, in which the same hemisphere always faces the star, resulting in perpetual day on one half of the planet and perpetual night on the other.

Computer simulations by a research group led by Ludmila Carone from the Max Planck Institute for Astronomy in Heidelberg show that a specific air current forms in the atmosphere of such planets. This current causes the ozone to accumulate in the equatorial region, while it is practically absent in all other regions. "If we can't detect ozone on a distant planet, that doesn't necessarily mean there's no oxygen there at all," Carone explains. "We might simply have looked in the wrong place – and the ozone is hiding elsewhere."

Nevertheless, astronomers are searching for a potential second Earth in M dwarf systems too, especially as these are much more common than stars that resemble our Sun. The Heidelberg Max Planck researchers have also been on a very special planetary hunt for a good two years now. Working with colleagues from other German and Spanish institutes, they have built an instrument that is studying around 300 M dwarfs using the largest telescope at Calar Alto Observatory in southern Spain and looking out for signs of rocky planets.

However, the James Webb Space Telescope is another source of great hope for astronomers. Launching in two years' time, at the earliest, this successor to Hubble will travel millions of kilometers from Earth on its mission to explore the universe. One of the prima-

Photo: Special Collections & Archives, UC San Diego Library

A gigantic compound eye: the gold-sputtered main mirror of the James Webb Space Telescope has a diameter of six and a half meters and is made up of 18 segments. From May 2020, at the earliest, the instrument will scour the heavens and train its sights on distant exoplanets.

ry objectives is to study exoplanets. The Max Planck Institute for Astronomy developed and built key components for one of the four measurement instruments, which goes by the name of MIRI, and so the Heidelberg astronomers will have the chance to make some of the first observations using the super telescope.

Like his colleague Oliver Trapp, Thomas Henning is also confident of the existence of life on faraway planets: "Simply by virtue of the enormous number of rocky planets in our Milky Way – perhaps as many as a billion – and the knowledge that life emerged very quickly on Earth, I think it's very likely that life exists on other planets." Are we therefore heading for a second Copernican Revolution? "No," replies Henning, "we're already in the midst of it." ◂

www.mpg.de/podcasts/
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Photo: NASA/Desiree Stover

SUMMARY

- **Today's life is based on the genetic information carrier DNA. As a forerunner to this, a world based on the simpler biomolecule RNA could have existed on the early Earth.**
- **The building blocks for RNA might have arrived on Earth inside meteorites. Computer simulations suggest that the subsequent synthesis of RNA began in pools measuring just a few meters in diameter.**
- **Using high-throughput screening, it is possible to test a very large number of chemical reactions in a short time and thus to narrow down the optimum conditions for the emergence of life.**

GLOSSARY

Electrolysis: Splitting of a chemical compound under the action of electrical current, resulting in the conversion of electrical energy into chemical energy. Electrolysis is the reverse reaction to that taking place in a battery or fuel cell.

Exoplanet: A planet outside the gravitational field of our Sun but within the gravitational field of another star. Around 3,800 exoplanets are currently known to astronomers.

Nucleobases: Constituents of nucleic acids such as DNA or RNA. DNA contains the nucleobases adenine, guanine, cytosine and thymine; in molecules of RNA, thymine is substituted for uracil. They are called bases because they dissolve in water to form weakly basic solutions. Adenine and thymine, as well as guanine and cytosine, each form base pairs, which then combine with the sugar molecule deoxyribose and a phosphate group to produce the basic backbone of the DNA double helix.