A role for meteoritic iron in the emergence of life on Earth

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A small fragment of the Campo del Cielo iron meteorite. The same intense heat that partially melted the meteorite to produce the smooth surface visible here would have also evaporated and ablated iron, creating tiny, nanometer-sized particles. These particles could have acted as catalysts for producing the building blocks of life on the early Earth. Credit: O. Trapp

Researchers from the Max Planck Institute for Astronomy and Ludwig Maximilians University Munich have proposed a new scenario for the emergence of the first building blocks for life on Earth, roughly 4 billion years ago.

By experiment, they showed how iron particles from meteors and from volcanic ash could have served as catalysts for converting a carbon-dioxide rich early atmosphere into hydrocarbons, but also acetaldehyde and formaldehyde, which in turn can serve as building blocks for fatty acids, nucleobases, sugars and amino acids. Their article, "Synthesis of prebiotic organics from CO_2 by catalysis with meteoritic and volcanic particles," is published in the journal *Scientific Reports*.

To the best of our current knowledge, life on Earth emerged a mere 400 to 700 million years after the Earth itself had formed. That is a fairly quick development. For comparison, consider that afterwards, it took about 2 billion years for the first proper (eukaryotic) cells to form. The first step towards the emergence of life is the formation of organic molecules that can serve as building blocks for organisms. Given how fast life itself arose, it would be plausible for this comparatively simple first step to have been completed quickly, as well.

The research described here presents a new way for such organic compounds to form on planetary scales under the conditions prevalent on the early Earth. The key supporting role goes to iron particles produced from meteorites, which act as a catalyst. Catalysts are substances whose presence speeds up specific chemical reactions, but which do not get used up in those reactions. In that way, they are akin to the tools used in manufacture: Tools are necessary to produce, say, a car, but after one car is built, the tools can be used to build the next one.

From industrial chemistry to the beginnings of the

Earth

Key inspiration for the research came, of all things, from industrial chemistry. Specifically, Oliver Trapp, a professor at Ludwig Maximilians University, Munich, and Max Planck Fellow at the Max Planck Institute for Astronomy (MPIA), wondered whether the so-called Fischer–Tropsch process for converting carbon monoxide and hydrogen into hydrocarbons in the presence of metallic catalysts might not have had an analog on an early Earth with a carbon-dioxide-rich atmosphere.

"When I looked at the chemical composition of the Campo-del-Cielo iron meteorite, consisting of iron, nickel, some cobalt and tiny amounts of iridium, I immediately realized that this is a perfect Fischer-Tropsch catalyst," explains Trapp. The logical next step was to set up an experiment to test the cosmic version of Fischer-Tropsch.

Dmitry Semenov, a staff member at the Max Planck Institute for Astronomy, says, "When Oliver told me about his idea to experimentally investigate the catalytic properties of iron meteorite particles to synthesize building blocks for life, my first thought was that we should also study the catalytic properties of volcanic ash particles. After all, the early Earth should have been geologically active. There should have been plenty of fine ash particles in the atmosphere and on Earth's first land masses."

Re-creating cosmic catalysis

For their experiments, Trapp and Semenov teamed up with Trapp's Ph.D. student Sophia Peters, who would run the experiments as part of her Ph.D. work. For access to meteorites and minerals, as well as expertise in the analysis of such materials, they reached out to mineralogist Rupert Hochleitner, an expert on meteorites at the

Mineralogische Staatssammlung in Munich.

The first ingredient for the experiments was always a source of iron particles. In different versions of the experiment, those iron particles might be iron from an actual iron meteorite, or particles from an iron-containing stone meteorite, or volcanic ash from Mount Etna, the latter as a stand-in for the iron-rich particles that would be present on the early Earth with its highly active volcanism. Next, the iron particles were mixed with different minerals such as might be found on the early Earth. These minerals would act as a support structure. Catalysts are commonly found as small particles on a suitable substrate.

Producing small particles

Particle size matters. The fine volcanic ash particles produced by volcanic eruptions are typically a few micrometers in size. For meteorites falling through the atmosphere of the early Earth, on the other hand, atmospheric friction would ablate nanometer-size iron particles. The impact of an iron meteorite (or of the iron core of a larger asteroid) would produce micrometer-sized iron particles directly through fragmentation, and nanometer-sized particles as iron evaporated in the intense heat and later-on condensed again in the surrounding air.

The researchers aimed to reproduce this variety of particle sizes in two different ways. By dissolving the meteoric material in acid, they produced nanometer-sized particles from their prepared material. And by putting either the meteoritic material or the volcanic ash into a ball mill for 15 minutes, the researchers could produce larger, micrometer-sized particles. Such a ball mill is a drum containing both the material and steel balls, which is rotated at high speeds, in this case more than ten times per second, with the steel balls grinding up the material.

Since Earth's initial atmosphere did not contain oxygen, the researchers then followed up with chemical reactions that would remove almost all of the oxygen from the mixture.

Producing organic molecules under pressure

As the last step in each version of the experiment, the mixture was brought into a pressure chamber filled with (mostly) carbon dioxide CO_2 and (some) hydrogen molecules, chosen so as to simulate the atmosphere of the early Earth. Both the exact mixture and the pressure were varied between experiments.

The results were impressive: Thanks to the iron catalyst, organic compounds such as methanol, ethanol and acetaldehyde were produced, but also formaldehyde. That is an encouraging harvest—acetaldehyde and formaldehyde in particular are important building blocks for fatty acids, nucleobases (themselves the building blocks of DNA), sugars and amino acids.

Importantly, these reactions took place successfully under a variety of pressure and temperature conditions. Sophia Peters says, "Since there are many different possibilities for the properties of the early Earth, I tried to experimentally test every possible scenario. In the end, I used fifty different catalysts, and ran the experiment at various values for the pressure, the temperature, and the ratio of carbon dioxide and hydrogen molecules." That the organic molecules formed under such a variety of condition is a strong indication that reactions like these could have taken place on the early Earth—whatever its precise atmospheric conditions will turn out to be.

Adding a scenario to the portfolio of possible mechanisms

With these results, there is now a new contender for how the first building blocks of life were formed on Earth. Joining the ranks of "classic" mechanisms such as organic synthesis near hot vents on the ocean floor, or electric discharge in a methane-rich atmosphere (as in the Urey-Miller experiment), and of models that predict how organic compounds could have formed in the depth of space and transported to Earth by asteroids or comets (see this MPIA press release), there is now another possibility: meteoric iron particles or fine volcanic ash acting as catalysts in an early, carbon-dioxide-rich atmosphere.

With this spread of possibilities, learning more about the atmospheric composition and physical properties of the early Earth should allow researchers to deduce, eventually, which of the various mechanisms will give the highest yield of building blocks under the given conditions—and which thus was likely the most important mechanism for the first steps from non-life to life on our home planet.

More information: Synthesis of prebiotic organics from CO_2 by catalysis with meteoritic and volcanic particles, *Scientific Reports* (2023). www.nature.com/articles/s41598-023-33741-8

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