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Formation of Earth and early life

Earth formation

Beginnings of life

Origins of life

Hypotheses about the origins of life

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Science • Biology • History of life on Earth • Formation of Earth and early life

Hypotheses about the origins of life

The Oparin-Haldane hypothesis, Miller-Urey experiment, and RNA world.

Key points:

- The Earth formed roughly 4.5 billion years ago, and life probably began between 3.5 and 3.9 billion years ago.
- The **Oparin-Haldane hypothesis** suggests that life arose gradually from inorganic molecules, with "building blocks" like amino acids forming first and then combining to make complex polymers.
- The **Miller-Urey experiment** provided the first evidence that organic molecules needed for life could be formed from inorganic components.
- Some scientists support the **RNA world hypothesis**, which suggests that the first life was self-replicating RNA. Others favor the **metabolism-first hypothesis**, placing metabolic networks before DNA or RNA.
- Simple organic compounds might have come to early Earth on meteorites.

Introduction

If there were other life out there in the universe, how similar do you think it would it be to life on Earth? Would it use DNA as its genetic material, like you and me? Would it even be made up of cells?

We can only speculate about these questions, since we haven't yet found any life forms that hail from off of Earth. But we can think in a more informed way about whether life might exist on other planets (and under what conditions) by considering how life may have arisen right here on our own planet.

In this article, we'll examine scientific ideas about the origin of life on Earth. The *when* of life's origins (3.5 billion years ago or more) is well-supported by fossils and radiometric dating. But the *how* is much less understood. In comparison to the central dogma or the theory of evolution, hypotheses about life's origins are much more...hypothetical. No one is sure which hypothesis is correct – or if the correct hypothesis is still out there, waiting to be discovered.

When did life appear on Earth?

Geologists estimate that the Earth formed around 4.5 billion years ago. This estimate comes from measuring the ages of the oldest rocks on Earth, as well the ages of moon rocks and meteorites, by radiometric dating (in which decay of radioactive isotopes is used to calculate the time since a rock's formation).

For many millions of years, early Earth was pummeled by asteroids and other celestial objects. Temperatures also would have been very high (with water taking the form of a gas, not a liquid). The first life might have emerged during a break in the asteroid bombardment, between 4.4 and 4.0 billion years ago, when it was cool enough for water to condense into oceans[1]. However, a second bombardment happened about 3.9 billion years ago. It's likely after this final go-round that Earth became capable of supporting sustained life.

The earliest fossil evidence of life

The earliest evidence of life on Earth comes from fossils discovered in Western Australia that date back to about 3.5 billion years ago. These fossils are of structures known as **stromatolites**, which are, in many cases, formed by the growth of layer upon layer of single-celled microbes, such as cyanobacteria. (Stromatolites are also made by present-day microbes, not just prehistoric ones.)

Image credit: "Stromatolite," by Didier Descouens, CC BY-SA 4.0.

The earliest fossils of microbes themselves, rather than just their by-products, preserve the remains of what scientists think are sulfur-metabolizing bacteria. The fossils also come from Australia and date to about 3.4 billion years ago[2].

Bacteria are relatively complex, suggesting that life probably began a good deal earlier than 3.5 billion years ago. However, the lack of earlier fossil evidence makes pinpointing the time of life's origin difficult (if not impossible).

How might life have arisen?

In the 1920s, Russian scientist Aleksandr Oparin and English scientist J. B. S. Haldane both separately proposed what's now called the **Oparin-Haldane hypothesis**: that life on Earth could have arisen step-by-step from non-living matter through a process of "gradual chemical evolution." [3]

Oparin and Haldane thought that the early Earth had a reducing atmosphere, meaning an oxygen-poor atmosphere in which molecules tend to donate electrons. Under these conditions, they suggested that:

- Simple inorganic molecules could have reacted (with energy from lightning or the sun) to form building blocks like amino acids and nucleotides, which could have accumulated in the oceans, making a "primordial soup." [3]

- The building blocks could have combined in further reactions, forming larger, more complex molecules (polymers) like proteins and nucleic acids, perhaps in pools at the water's edge.

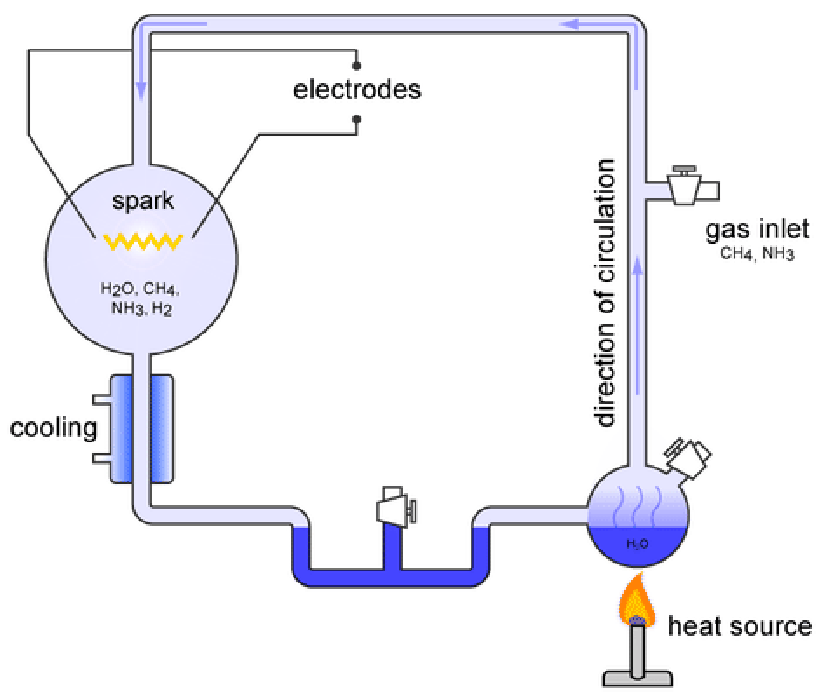
- The polymers could have assembled into units or structures that were capable of sustaining and replicating themselves. Oparin thought these might have been "colonies" of proteins clustered together to carry out metabolism, while Haldane suggested that macromolecules became enclosed in membranes to make cell-like structures[4,5].

The details of this model are probably not quite correct. For instance, geologists now think the early atmosphere was not reducing, and it's unclear whether pools at the edge of the ocean are a likely site for life's first appearance. But the basic idea – a stepwise, spontaneous formation of simple, then more complex, then self-sustaining biological molecules or assemblies – is still at the core of most origins-of-life hypotheses today.

From inorganic compounds to building blocks

In 1953, Stanley Miller and Harold Urey did an experiment to test Oparin and Haldane's ideas. They found that organic molecules could be spontaneously produced under reducing conditions thought to resemble those of early Earth.

Miller and Urey built a closed system containing a heated pool of water and a mixture of gases that were thought to be abundant in the atmosphere of early earth (H_2O, NH_4, CH_4, and N_2). To simulate the lightning that might have provided energy for chemical reactions in Earth's early atmosphere, Miller and Urey sent sparks of electricity through their experimental system.



After letting the experiment run for a week, Miller and Urey found that various types of amino acids, sugars, lipids and other organic molecules had formed. Large, complex molecules like DNA and protein were missing, but the Miller-Urey experiment showed that at least *some* of the building blocks for these molecules could form spontaneously from simple compounds.

Were Miller and Urey's results meaningful?

Scientists now think that the atmosphere of early Earth was different than in Miller and Urey's setup (that is, not reducing, and not rich in ammonia and methane)[6,7]. So, it's doubtful that Miller and Urey did an accurate simulation of conditions on early Earth.

However, a variety of experiments done in the years since have shown that organic building blocks (especially amino acids) can form from inorganic precursors under a fairly wide range of conditions[8]. *[What about nucleotides?]*

From these experiments, it seems reasonable to imagine that at least some of life's building blocks could have formed abiotically on early Earth. However, exactly how (and under what conditions) remains an open question.

From building blocks to polymers

How could monomers (building blocks) like amino acids or nucleotides have assembled into polymers, or actual biological macromolecules, on early Earth? In cells today, polymers are put together by enzymes. But, since the enzymes themselves are polymers, this is kind of a chicken-and-egg problem!

Monomers may have been able to spontaneously form polymers under the conditions found on early Earth. For instance, in the 1950s, biochemist Sidney Fox and his colleagues found that if amino acids were heated in the absence of water, they could link together to form proteins[10]. Fox suggested that, on early Earth, ocean water carrying amino acids could have splashed onto a hot surface like a lava flow, boiling away the water and leaving behind a protein.

Image credit: "Kusový montmorillonit," by Jan Kameníček, CC BY-SA 3.0.

Additional experiments in the 1990s showed that RNA nucleotides can be linked together when they are exposed to a clay surface[11]. The clay acts as a catalyst to form an RNA polymer. More broadly, clay and other mineral surfaces may have played a key role in the formation of polymers, acting as supports or catalysts. Polymers floating in solution might have hydrolyzed (broken down) quickly, supporting a surface-attached model[12].

The image above shows a sample of a type of clay known as montmorillonite. Montmorillonite in particular has catalytic and organizing properties that may have been important in the origins of life, such as the ability to catalyze formation of RNA polymers (and also the assembly of cell-like lipid vesicles)[13].

What was the nature of the earliest life?

If we imagine that polymers were able to form on early Earth, this still leaves us with the question of how the polymers would have become self-replicating or self-perpetuating, meeting the most basic criteria for life. This is an area in which there are many ideas, but little certainty about the correct answer.

The "genes-first" hypothesis

One possibility is that the first life forms were self-replicating nucleic acids, such as RNA or DNA, and that other elements (like metabolic networks) were a later add-on to this basic system. This is called the **genes-first** hypothesis[14].

Many scientists who subscribe to this hypothesis think that RNA, not DNA, was likely the first genetic material. This is known as the **RNA world hypothesis**. Scientists favor RNA over DNA as the first genetic molecule for several reasons. Perhaps the most important is that RNA can, in addition to carrying information, act as a catalyst. In contrast, we don’t know of any naturally occurring catalytic DNA molecules[15,16].

RNA catalysts are called **ribozymes**, and they could have played key roles in the RNA world. A catalytic RNA could, potentially, catalyze a chemical reaction to copy itself. Such a self-replicating RNA could pass genetic material from generation to generation, fulfilling the most basic criteria for life and, potentially, undergoing evolution. In fact, researchers have been able to synthetically engineer small ribozymes that are capable of self-replication.

[Relics of the RNA world in present-day cells?]

It’s also possible that RNA wasn’t the first information-carrying molecule to serve as genetic material. Some scientists think that an even simpler “RNA-like” molecule with catalytic and information-carrying capacity might have come first, and might have catalyzed or acted as a template for RNA synthesis. This is sometimes called the "pre-RNA world" hypothesis[17].

The "metabolism-first" hypothesis

An alternative to the genes-first hypothesis is the **metabolism-first** hypothesis, which suggests that self-sustaining networks of metabolic reactions may have been the first simple life (predating nucleic acids)[14,18].

These networks might have formed, for instance, near undersea hydrothermal vents that provided a continual supply of chemical precursors, and might have been self-sustaining and persistent (meeting the basic criteria for life). In this scenario, initially simple pathways might have produced molecules that acted as catalysts for the formation of more complex molecules[18]. Eventually, the metabolic networks might have been able to build large molecules such as proteins and nucleic acids. Formation of "individuals" enclosed by membranes (separate from the communal network) would have been a late step[14].

What might early cells have looked like?

A basic property of a cell is the ability to maintain an internal environment different from the surrounding environment. Today’s cells are separated from the environment by a phospholipid bilayer. It’s unlikely that phospholipids would have been present under the conditions in which the first cells formed, but other types of lipids (ones that would have more likely been available) have also been shown to spontaneously form bilayered compartments[19].

In principle, this type of compartment could surround a self-replicating ribozyme or the components of a metabolic pathway, making a very basic cell. Though intriguing, this type of idea is not yet supported by experimental evidence – i.e., no experiment has yet been able to spontaneously generate a self-replicating cell from abiotic (non-living) components.

Another possibility: Organic molecules from outer space

Organic molecules might have formed spontaneously from inorganic ones on early Earth, *à la* Miller-Urey. But could they instead have come from space?

The idea that organic molecules might have traveled to Earth on meteorites may sound like science fiction, but it's supported by reasonable evidence. For example, scientists have found that organic molecules can be produced from simple chemical precursors present in space, under conditions that could exist in space (high UV irradiation and low temperature)[20]. We also know that some organic compounds are found in space and in other star systems.

Most importantly, various meteorites have turned out to contain organic compounds (derived from space, not from Earth). One meteorite, ALH84001, came from Mars and contained organic molecules with multiple ring structures. Another meteorite, the Murchison meteorite, carried nitrogenous bases (like those found in DNA and RNA), as well as a wide variety of amino acids.

Image credit: "ALH84001 meteorite, on display at Smithsonian Museum of Natural History," by J. L. Stuby, CC BY-SA 3.0.

One meteorite that fell in 2000 in Canada contained tiny organic structures dubbed "organic globules." NASA scientists think this type of meteorite might have fallen to Earth often during the planet's early history, seeding it with organic compounds[21].

[Could life itself have come from elsewhere in the universe?]

Summary

How life originated on our planet is both a fascinating and incredibly complex question. We know roughly *when* life began, but *how* remains a mystery.

- Miller, Urey, and others showed that simple inorganic molecules could combine to form the organic building blocks required for life as we know it.

- Once formed, these building blocks could have come together to form polymers such as proteins or RNA.

- Many scientists favor the RNA world hypothesis, in which RNA, not DNA, was the first genetic molecule of life on Earth. Other ideas include the pre-RNA world hypothesis and the metabolism-first hypothesis.
- Organic compounds could have been delivered to early Earth by meteorites and other celestial objects.

These are not the only scientific ideas about how life might have originated, nor are any of them conclusive. Keep your ears (and your mind) open as new information becomes available and new scientific ideas are proposed concerning life's origins.

[References]

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Questions Tips & Thanks

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Trey Thompson 3 years ago more

Could another experiment much like the Miller-Urey experiment be conducted again with slightly different components today? If so, could we learn anything new from it?

Reply • Comment (4 votes) Upvote Downvote Flag m...

Travis Fisher 3 years ago more

Clicking on the expandable 'What about Nucleotides?' link revealed an answer to your question. It's noted that "one recent study using a different approach (not an approach similar to Miller and Urey) found that RNA nucleotides could be formed from inorganic components under conditions thought to resemble those of early Earth."

1 comment (6 votes) Upvote Downvote Flag m...

Bintia Diallo 3 years ago more

Does it mean that DNA is the evolution of RNA?
Is it possible that Panspermia and Abiogenesis happened at the same time ?

Reply • Comment (4 votes) Upvote Downvote Flag m...

++§ Αλεκσανδαρ 3 years ago more

Hi, Bintia and thank you for your questions.

DNA evolved from RNA, that's our current belief. When i was a student i was constantly searching for some kind of info on that process (in other words, how did DNA became from RNA) but i found almost nothing. Some scientists believe that viruses "invented" DNA because they are the only "living" beings who have both RNA and / DNA for their genetic material.

I would say it is possible that panspermia and abiogenesis happened at the same time, however we can only speculate about that. Abiogenesis might be still happening in some obscure thermal vents somewhere in the depths of oceans, who knows.

1 comment (3 votes) Upvote Downvote Flag m...

gpemilie a year ago more

Since there is so much diversity on Earth,is it more or less likely to have an 'origin of life' event today than 4 billion years ago? Is there a limit to mutations?

Reply • Comment (2 votes) Upvote Downvote Flag m...

tyersome a year ago more

We think that any newly originated organism (or proto- organism) would be very unsophisticated and unlikely to survive competition with existing organisms. This suggests that successful "origin of life" events (i.e. where the new organisms persist in the environment) are very unlikely.

Beyond that, we aren't sure exactly what needs to happen for an "origin of life" event to occur so it is difficult to know whether current conditions would enhance or inhibit these events.

We do know that the early earth's atmosphere was reducing (didn't contain oxygen) and it is quite possible that oxygen would interfere with the chemistry necessary for an "origin of life", so my *guess* is that a new "origin of life" is unlikely on this planet ...

Comment (3 votes) Upvote Downvote Flag m...

hemmjesslucio 3 years ago more

Why is it that the RNA world hypothesis is more favored over the Metabolism-first hypothesis? (In other words, how is the RNA hypothesis more reasonable?)

Reply • Comment (3 votes) Upvote Downvote Flag m...

++§ Αλεκσανδαρ 3 years ago more

I assume that's because RNA molecules have many abilities and in general have more diverse functions than proteins. RNA can be a genetic molecule (like in some viruses), it can epigenetically control the expression of genes (like micro-RNA molecules), it can have enzymatic abilities (like ribozymes) and so on. Proteins, on the other hand are mostly known as enzymes.

So, from our current perspective, it looks like an RNA molecule had better chances of catalyzing its own replication because, in theory, it can do that. Proteins are good enzymes, but they can't serve as genetic material and therefore they can't make copies of themselves.

I should also note that the discovery of prions in 1980's dramatically changed our view on the topic. It happened in the moments when most people in the scientific community already declared RNA's as winners in the battle against proteins but then, all of a sudden, Stanley Prusiner discovered proteins that can turn other (but similar) proteins into their own clones.

Even though it still looks like RNA molecules are better candidates, the battle is still going on.

Comment (1 vote) Upvote Downvote Flag m...

Sanehdeep Kaur 3 years ago more

What are the three materials would the early cells need to have to become self-sustaining?

Reply • Comment (3 votes) Upvote Downvote Flag m...

Ivana - Science trainee 6 months ago more

Materials....do you think parts of the cell or chemicals? I'd say cell membrane, cytoplasm, and nucleus.

Comment (1 vote) Upvote Downvote Flag m...

Cristopher 4 years ago more

On the 21st part of this article itroduses a new theory. Thet the organic molecules came out of the planet but, if this its true from where did they came from?

Reply • Comment (2 votes) Upvote Downvote Flag m...

Davin V Jones 4 years ago more

As the article also states, they formed from inorganic molecules.

Comment (3 votes) Upvote Downvote Flag m...

chrslnascr31 a year ago more

Do you believe that the diversity we see around us comes from a single 'origin of life' event or multiple 'origin of life' events?

Reply • Comment (2 votes) Upvote Downvote Flag m...

tyersome

a year ago

more

All life on earth appears to be related — this is based on the presence of ancient genes that are found in (essentially) all living organisms.

This progenitor of all known life is referred to as the "Last universal common ancestor" (LUCA).

You can start learning more about this here:
https://en.wikipedia.org/wiki/Last_universal_common_ancestor

Comment (2 votes) Upvote Downvote Flag m...

charlietheteacher4jc a year ago

more

How is it that the RNA World hypothesis is still being considered? See this article from retraction watch:
https://retractionwatch.com/2017/12/05/definitely-embarrassing-nobel-laureate-retracts-non-reproducible-paper-nature-journal/

Reply • Comment (1 vote) Upvote Downvote Flag m...

tyersome a year ago

more

A quick search of pubmed for the phrase "RNA world" finds 914 papers:
https://www.ncbi.nlm.nih.gov/pubmed/?term=%22RNA+world%22

Why do you think retraction of a single paper (about one possible contributor to a protein independent RNA replication) invalidates this hypothesis?

If you are really interested in this subject I encourage you to start learning more by looking at some of the references at the bottom of this article.

Two examples:
• http://www.ncbi.nlm.nih.gov/books/NBK26876/

• http://evolution.berkeley.edu/evolibrary/article/ellington_03

3 comments (4 votes) Upvote Downvote Flag m...

Flindersuniversitymaryam 4 years ago

more

what is difference between Miller and Operian hypotheses and who was right?

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Darmon 4 years ago

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The Operian hypothesis suggests that simple, inorganic molecules gave rise to more complex organic ones (such as amino acids), and then those combined to create the most complex molecules of life (such as proteins). Miller and Urey, on the other hand, performed an experiment in which they simulated an early earth environment and proved that small inorganic compounds can combine to create more complex organic ones under such conditions. In short, the Miller experiment provided scientific support for the Operian hypothesis.

Comment (2 votes) Upvote Downvote Flag m...

mattwilsonmbw 2 years ago

more

The article says: "In fact, researchers have been able to synthetically engineer small ribozymes that are capable of self-replication."

This seems very interesting and I wanted to read more about it, but there is not a citation. Can anyone point to what work this refers to? Thanks.

Reply • Comment (1 vote) Upvote Downvote Flag m...

Davin V Jones 2 years ago

more

Not sure if this is their specific reference, but here is a journal article:
http://www.pnas.org/content/99/20/12733

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‹ Origins of life