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Research Article

How did Life Begin? A Review of the Environmental and Biomolecular Hypotheses Surrounding Abiogenesis

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ABSTRACT

Abiogenesis is the scientific theory that all life evolved from no life and is widely agreed to be correct. However, there are debating schools of thought about how and where life was initially synthesised, and what the first biomolecule was. This literature review will analyse the scientific papers and journals relating to these theories in order to discuss how probable they are. It will also compare different theories, as the environment may affect which biomolecule was first synthesised. It will also discuss external factors, such as meteorites, and how they influence the hypotheses. The environments under review are deep-sea vents, primordial soups and celestial bodies; and the biomolecules discussed are RNA and Proteins. This review will also touch on whether metabolism came about before the biomolecules of life. From analysis of the literature, it seems likely that RNA was the initial biomolecule. It must, however, be mentioned that this review cannot come to a clear conclusion in answer to the question 'how did life begin?', as we cannot know for sure the environmental composition of primitive earth.

INTRODUCTION

'How did life begin?', a question that has plagued the minds of humans for centuries. Many early hypotheses are outdated, but these must be acknowledged to understand the modern theories of how life on earth started. In ancient Greece, Aristotle suggested the first major theory for abiogenesis; Spontaneous Generation, and for a long time this was widely regarded as correct[1]. Aristotle's observations led to the idea that decaying organisms produced new life, for example, it was logical for Aristotle to believe that flies evolved from rotten substances after studying decaying meats[2]. Aristotle's abiogenesis theory was contested by numerous scientists up to the 19th century; Redi and Pasteur both carried out experiments that lead them to disprove spontaneous generation in favour of biogenesis (life from life)[3],[4]. Pasteur's experiments were designed to determine whether organisms such as fungi and bacteria would spontaneously appear in sterile environments. When they failed to do so, he ruled Spontaneous Generation impossible[3]. Redi showed that flies did not spontaneously arise from rotting meat, refuting Aristotle[4]. Until Darwin initiated the first discussion of life beginning from the later named 'primordial soup', Spontaneous Generation, though long debated, had no significant opposing theory. Like Aristotle, Darwin believed that life came from no life, but his belief was that this interaction only occurred once, billions of years ago, producing the bare organic molecules[5]. Darwin argued that after this initial production of organic material, evolution took over [6]. In 1967, Bernal proposed that three evolutionary stages occurred after the initial production of organic material: Initially, biological monomers existed, which led to biological polymers, leading to the production of cells from molecules[7].

Most respected, modern theories echo Darwin's belief that life began from a series of reactions triggering production of organic matter from non-organic material. Four categories of biological molecule exist: carbohydrates, lipids, proteins and nucleic acids; and many schools of thought exist debating which occurred first. Recent discussions also debate the environment in which these molecules were first produced. This review will discuss various theories and their relation to celestial bodies.

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ENVIRONMENT

The Primordial Soup

The theories surrounding the environment of organic molecule initial production are perhaps the most common. The ‘primordial soup’ hypothesis, presented by Oparin in 1924, uses Darwin’s belief that organic matter was produced from a non-organic pool of chemicals on the surface of the earth[8]. Oparin’s work was all theoretical; no research was carried out to test his hypothesis. His theory introduced the idea that earth possessed a different atmosphere to what it has now, and this mix of materials could have formed basic organic molecules. Earth’s atmosphere currently consists mainly of nitrogen, but with a large amount of oxygen (21%). Also present are minute amounts of CO2, H2O, and argon[9]. On early earth, the atmosphere was thought to contain compounds such as methane and ammonia which resulted in an oxygen-deficient environment. This gives us the first introduction to the usefulness of cosmic bodies in determining how life began; Oparin became aware of the existence of different cosmic atmospheres and environments as at this time methane had been discovered in the atmospheres of many large cosmic bodies. This thinking has gained credibility more recently as later studies have determined the exact chemical make- up of Jupiter’s atmosphere[10]. The composition of the atmosphere of other planets may indicate what may have been on earth before the presence of oxygen-producing organisms.

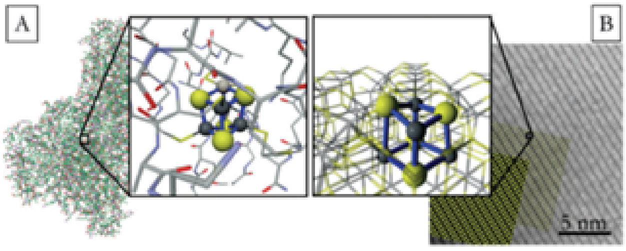
The ‘Primordial soup’ theory gained major traction due to Urey and Miller. In 1952, they carried out experiments inspired by Oparin’s hypothesis to emulate the conditions of the early atmosphere, with the purpose to see if they could recreate the shift from inorganic to organic molecules. An apparatus circulating CH4, NH3, H2 and H2O over an electrical discharge produced a liquid solution, and paper chromatography was used to identify the constituents of this solution. Identified with this technique were Glycine and a/b-alanine, supporting the ‘primordial soup’ hypothesis[11]. Methane, ammonia, hydrogen, and water vapour, as ingredients in earths ‘primordial soup’, may have led to the formation of amino acids[11]. However, this hypothesis could also provide evidence for RNA-first; after adapting the experiment of Urey and Miller, the nucleic acid adenine was produced in 1961 by Joan Oro[12]. This theory encourages both the protein and RNA-first theory, however, there is evidence for other origins of proteins and nucleic acids that will be discussed later.

The credibility of the ‘primordial soup’ theory is questioned by insights into meteoric activity and earth environment during the primordial soup era. Earth’s climate 4 billion years ago would not have been suitable for almost any early organism to flourish due to the ‘catastrophic meteorite bombardment’. As meteorites land, the atmosphere increases in temperature, and each one has the ability to vaporise any water on the earth’s surface. Any life produced would have been destroyed in the incineration of the oceans and resulting erratic climate[13]

Deep Sea Events

A contrasting theory debates that organic matter began in deep sea vents inside the earth. This is plausible, as the meteorite showers that would destroy life on the surface would not affect the environment of the deep sea. Though lacking the support ‘primordial soup’ has acquired in the past 100 years, the recent discovery of submarine geothermal pockets gives a new take on the environment in which organic molecules appeared. H2, CH4 and NH3 are found within these vents, implying that the reactions that occurred in Urey-Miller could potentially occur in a different environment[14]. The energy that would be required for the production of organic molecules is present in the form of hot, turbulent water[15]. The ocean has a better environment for abiogenesis compared to the surface as the physio-chemistry of the ocean floor is stable and unchanging, lending itself to the production of organic molecules[13]. Within some of these vents exist minerals such as the iron sulfite Greigite (Fe3S4). These minerals have catalytic activity that echoes present day enzymes; the ability to produce small organic molecules, such as methanol, formic acid, acetic acid and pyruvic acid, from CO2 (figure 1)[15]. Chemical compounds with enzymatic properties add reasoning behind the belief that it is possible life began from biochemical precursors within submarine vents. The small organic molecules produced, once reacted with ammonia present, can become biomolecules.

Figure 1: A) Representation of the ferredoxin centre of the CO dehydrogenase enzyme, B) the greigite surface, Fe3S4(001), showing enhanced cubane structure.



The presence of formic, pyruvic and acetic acid supports the hypothesis that the basic metabolism may have been the first biological process to occur, and that RNA and proteins were produced after the metabolic compounds. As they are important components of the Krebs cycle, which is important in biological systems due to its production of ATP, it is sensible to propose that the acids present in hydrothermal vents may have led to an initial basic metabolism that life evolved from.

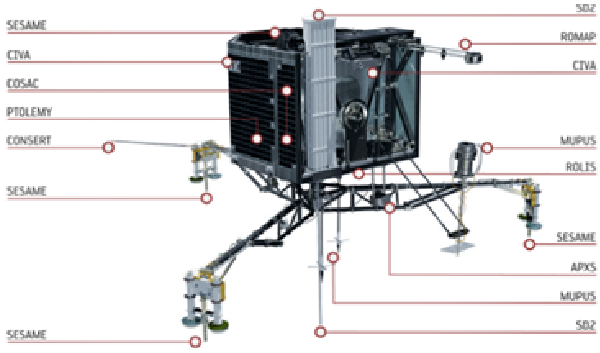
Meteorites

There is evidence that biomolecules exist on meteorites, and therefore the precursors to life may have begun within our solar system[16]. No matter which biomolecule came first, there is an abiogenesis argument that instead of being first synthesised on earth, RNA and amino acids were brought to the surface on meteorites. The meteorite bombardment 4 billion years ago could have brought these basic biomolecules. Chamberlin and Chamberlain were the first to suggest that a large proportion of earth’s biomolecule precursors such as RNA and amino acids may have been delivered by meteorites and asteroids[17]. This theory is not without faults however as models suggest amino acids have a low chance of surviving the erratic environments and high temperatures of the shock, which proves to decompose organic matter. This matter can be delivered from space via interplanetary dust particles (IDPs) which would allow the amino acids to enter the atmosphere without destruction[17]. The recent evidence of amino acids discovered in meteorites helps build credibility back up that organic matter could have entered from space, although it could be from IDP's settling on the meteorite once it landed. In 2002, an assay was carried out to prove amino acids could be produced in interstellar environments. The laboratory reproduced these environments and proved that amino acids could have been produced in the same conditions of outer space[18]. This gives evidence towards amino acids being introduced to earth via IDP.

The Murchison meteorite of 1969 is of the class carbonaceous chondrite, is well studied, and used to give evidence that life precursors may have been introduced from meteorites. Murchison contains amino acids, amino acid precursors, and organic compounds such as amines and monocarboxylic acids[19]. The presence of amino acids allows for the theory that proteins could have been the first biomolecules in evolution, with the amino acid precursors delivered on meteorites. Analysis of these amino acids confirmed that they were the product of interstellar synthesis; the high nitrogen isotope ratio present in the amino acids matches the ratio of known outer space compounds, proof that these amino acids were not the result of contamination events or terrestrial origin. The Murchison meteorite also contained evidence of nucleobases, the building block of RNA. Similar isotopic ratio analysis as above was used, using carbon instead of nitrogen, to confirm the extra-terrestrial origin of the nucleobases[20].

There is also evidence from meteorites that haven't landed, CHO containing organic compounds were identified from comet 67P/Churyumov- Gerasimenko whilst in orbit.

Figure 2: An annotated image of the Rosetta lander, with the Ptolemy drill and COSAC (evolved gas analysers) labelled on the mid-right[21]



To obtain the sample, a Ptolemy drill within the Rosetta lander (figure 2) landed on the comet and collected samples from both the surface of the comet and within. COSAC Mass Spectrometry of the samples showed 16 different compounds from various molecular families. This form of mass spectrometry is particular to interstellar examination: Cometary sampling and composition studies. An issue with COSAC Mass Spectrometry is its resolution of 300, which leads to no distinction between peaks of the same mass. Also, analysis could not be done on peaks above 62m/z due to the interference of noise. In order for the results to be viable and respected, in-depth analysis and manipulation of initial spectroscopy data received by the Ptolemy drill was carried out. This resulted in a clear mass spectrometer graph, with peaks for each of the 16 compounds displayed relative to water (figure 3)[22].

Figure 3: Graph to show comparison of the original COSAC values and the values after analysis and reconstruction against water at 100.

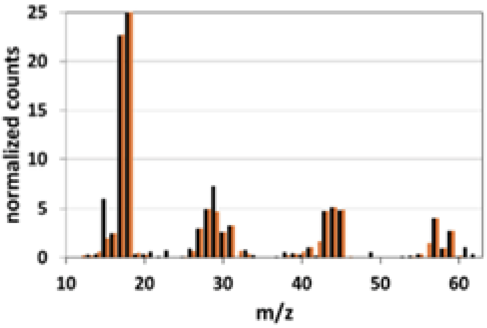


Figure 4: Figure to show 16 molecules discovered on comet 7P/ Churyumov- Gerasimenko. Figure also shows data from figure 2 [22].

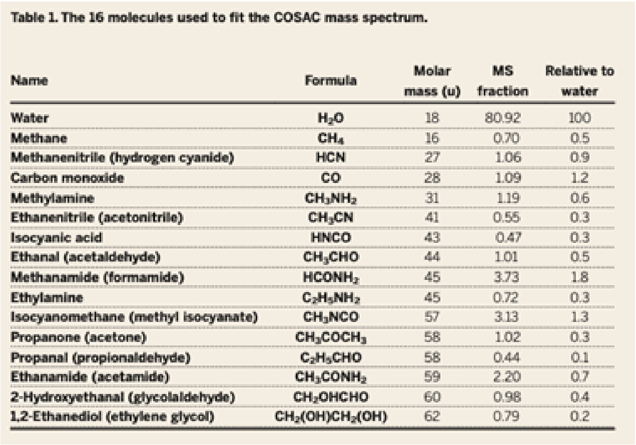


Table 1. The 16 molecules used to fit the COSAC mass spectrum.

Name	Formula	Molar mass (u)	MS fraction	Relative to water
Water	H_2O	18	80.92	100
Methane	CH_4	16	0.70	0.5
Methanenitrile (hydrogen cyanide)	HCN	27	1.06	0.9
Carbon monoxide	CO	28	1.09	1.2
Methylamine	CH_3NH_2	31	1.19	0.6
Ethanenitrile (acetonitrile)	CH_3CN	41	0.55	0.3
Isocyanic acid	HNCO	43	0.47	0.3
Ethanal (acetaldehyde)	CH_3CHO	44	1.01	0.5
Methanamide (formamide)	$HCONH_2$	45	3.73	1.8
Ethylamine	$C_2H_5NH_2$	45	0.72	0.3
Isocyanomethane (methyl isocyanate)	CH_3NCO	57	3.13	1.3
Propanone (acetone)	CH_3COCH_3	58	1.02	0.3
Propanal (propionaldehyde)	C_2H_5CHO	58	0.44	0.1
Ethanamide (acetamide)	CH_3CONH_2	59	2.20	0.7
2-Hydroxyethanal (glycolaldehyde)	CH_2OHCHO	60	0.98	0.4
1,2-Ethanediol (ethylene glycol)	$CH_2(OH)CH_2(OH)$	62	0.79	0.2

Some of the compounds discovered are precursors for major biomolecules: Hydrogen Cyanide is particularly useful as there is theory that it is the basis of synthesis of all nucleobases (except thymine), and amino acids[23]. The discovery of various compounds is evidence enough that the origin of life may have been extra-terrestrial, be it as nucleobases, amino acids, or as the precursor organic compounds.

BIOMOLECULE

RNA

Alongside those debating where life first began are those concentrating on which biomolecule was first produced, or whether organic molecules used in metabolism were synthesised first. RNA is believed to have come first in a theory referred to as ‘RNA-world’. For life to exist, there must be nucleic acids and a molecule with enzymatic abilities. Originally, scientists believed that this meant RNA and proteins must have existed simultaneously in order for replication to occur. The structures of nucleic acids were first discovered in 1953 by Crick, Watson, and Franklin. Their discovery of DNA’s structure led to increased understanding of the nucleic acids and RNA. Crick discussed RNA and the primitive coding in his paper ‘The origin of the genetic code’. He noticed the necessary involvement of RNA in protein synthesis. The ribosome (RNA with enzymatic activity) and tRNA are required for the peptide synthesis in all organisms. If RNA is so vital, does protein fit in the primitive mechanism?[24].

In E. coli, a ribonuclease has the machinery to cleave phosphodiester bonds during RNA maturation[25]. The identification of an RNA with enzymatic activity implies that there might exist an RNA with the machinery to catalyse the synthesis of a new RNA strand. If this is the case, proteins are made redundant and RNA could exist in solitary; initially self-assembling from nucleic acids then replicating and mutating to evolve. The cofactors required to have full enzymatic activity, such as NADH, would have to be present in order for RNA to be self-replicating. These molecules have the same basic structure as nucleic acids, showing that they may have evolved simultaneously[26]. Hans von Euler-Chelpin discovered that NADH consists of an adenine and a nicotinamide bound together, giving the theory that NADH were present before proteins credibility[27]. For RNA to be the initial biomolecule, nucleobases must have existed previously. Orgel proposed a theory that RNA was preceded by a simpler nucleic acid[28].

Protein

In order to discuss a world where nucleic acids exist without proteins, there must always be discussion of an environment where proteins and amino acids exist without nucleic acids. Orgel not only discusses RNA, but the primitive environment of a protein-only kingdom[28]. The primordial soup theory has maybe the strongest support due to its fame, but there is other evidence that proteins and amino acids may have existed pre nucleic-acid-based molecules. The evidence of amino acids on meteorites allows the debate that protein precursors arrived to early earth as opposed to being synthesised here.

Both

Recently, discoveries into primitive proteins have begun to suggest an RNA-Protein-world, where they evolved with each other[29]. In 2013, Li, Francklyn, and Carter Jr. studied Class I TrpRS and Class II HisRS Urzymes. Urzymes are ‘primitive plus enzymes’ derived from amino-acyl-tRNA synthetases and are proven to acylate tRNAs at 106 times faster than the non-catalysed ribosome-independent reaction. This reaction gave data to show the similarities of catalytic ability of Urzymes from well before the evolution and assembly of full-length enzymes, to now. The Urzymes seem to predate modern aaRS whilst simultaneously being highly evolved, their complex catalytic capacity and the interaction with tRNA allows for the theory that Urzymes co-evolved with tRNA instead of RNA synthesis occurring first, and proteins next.

CONCLUSION

The literature regarding ‘How did life begin?’ cannot be held to the standard that the most recent findings are the most correct as the question asks about scientific processes that occurred millions of years ago. Any studies in the last hundred years have a basis in understanding the environment of primitive earth, an environment which, however much speculation occurs, cannot be proven without dispute. Any findings about whether RNA or protein came first, or where the precursors originated, must be taken with reservations. The science may be accurate, but there is no proof it actually occurred and initiated life as we know it today.

After reviewing the literature, there is the strongest evidence for RNA-world. It seems that the activity of RNA is the most comprehensive of all the biomolecules; RNA has the capability for self-replication, whereas proteins do not, and RNA can act as proteins, whereas proteins cannot store genetic information. By introducing outer space as a new possible environment for the origin of life, the hope of this review is to look at the age-old question through a new and unique lens. Celestial bodies can help with some understanding of the origins of life due to their similar environments to early earth, giving a unique insight into what the terrestrial surface and atmosphere may have been. The next review step I would recommend is to study literature on other interstellar bodies that have environments unchanged in the last 3.8 million years due to their age and lack of organic interference, which can give more specific insights into the composition of early earth.

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