The Miller-Urey Experiment and the Existence of Life on Mars

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Abstract

Harold Urey proposed a series of conditions, which, if present on prebiotic Earth, would have been conducive to the origins of life on Earth. Stanley Miller later proved that these conditions were favorable for the synthesis of simple amino acids, which was the beginning of a series of experiments, modeled on this notion of prebiotic Earth, that created other more complex molecules needed to support life. Using the hypothesis set up by Urey and tested by Miller, this paper looks at whether these prebiotic conditions ever existed on the surface of Mars, thus making it possible to have or have had life on Mars.

1. Introduction

Since the dawn of civilization, humanity has watched the brilliant red wanderer in the night sky, always fascinated, always wondering, and always striving to know more. Whether or not there was life on Mars was a question even before Lowell imagined advanced civilizations building complex canal systems. Comparisons were constantly being drawn between Earth and her red sister. If life existed on Mars, where did it come from? Perhaps Earth and Mars were indeed similar, and however life had begun on Earth was the same mechanism by which life began on Mars. Thus, if it were possible to know the conditions that had been conducive to life on Earth, and if those same conditions ever existed on Mars, it might be possible to predict whether or not life could have ever formed on the surface of Mars.

As far as human knowledge currently extends, life only exists in one carbon-based form, with all life forms sharing the common building blocks of amino acids, proteins, and nucleic acids. If this is indeed the only type of life form that can exist, then it can be assumed that any life on Mars would have to be of this type as well. It is then possible to compare any possible life on Mars to life on Earth. Currently it is not absolutely known where, when, or how life on Earth originated, though three main theories exist (Sharma, 2003). First, life may have originated elsewhere in the universe, transported to the Earth by meteorite or comet, a theory known as panspermia. A second theory proposes that life began in hydrothermal systems on the ocean bottom, where the Earth's crust is constantly, albeit slowly, recycled and regenerated. The third theory, and the one examined by this paper, is that life began in a sort of prebiotic "soup" when the Earth was warm and wet several billions of years ago. Although this theory forms the basis for this paper, it should be noted that as a more in depth understanding of the solar system is acquired, the likelihood that life began in this manner becomes less and less. As evidence collected during the Apollo lunar missions indicates, the Earth's atmosphere at the time life began probably did not fit the conditions necessary (Drury, 1999; 204).

2. The Origin of Life

"It must be admitted from the beginning that we do not know how life began."
-Stanley Miller and Leslie Orgel

Aleksandr Oparin first proposed the idea that life could originate on the surface of prebiotic Earth in his book, *The Origin of Life* in 1938 (Miller and Horowitz, 1966; 49). He proposed that the atmospheric conditions would need to be reducing in order for this to occur, an idea later backed by Harold Urey in 1952 (Miller and Horowitz, 1966; 49). Urey went on to show that not only would a reducing atmosphere exist, but the most thermodynamically stable forms of carbon and nitrogen would be methane and ammonia respectively, proven by the following reactions, where the equilibrium constant drives each reaction towards the products: (Miller and Urey, 1966; 186)

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

$$CaSiO_3 + CO_2 \rightleftharpoons CaCO_3 + SiO_2$$

$$\tfrac{1}{2} N_2 + \tfrac{3}{2} H_2 \rightleftharpoons NH_3$$

This supported Oparin's hypothesis that methane and ammonia were present in the early Earth atmosphere, rather than the carbon dioxide and nitrogen that compose Earth's present atmosphere. Additionally, Urey also proposed that the surface of Earth would have been warm, although less than 100°Celsius, in order to allow liquid water to freely exist (Miller, 1966; 167).

2.1 Miller's Experiment

In 1953, Stanley Miller created these conditions in a closed system designed to resemble Urey's image of prebiotic Earth. Using the closed system, seen in Figure 1, Miller combined the hydrogen, ammonia, and methane gases that Oparin and Urey had predicted would be present in the prebiotic atmosphere with water. Using an electrical discharge, an energy source mimicking a lightning strike, Miller was able to create several amino acids inside the system, including glycine, α-alanine, β-alanine, and aspartic acid (Miller, 1953). Additionally, Miller detected the presence of hydrogen cyanide, formaldehyde, and acetaldehyde in the resultant mixture, indicating that these molecules had also been synthesized at some point during the reactions (Miller, 1966; 170). These molecules, especially hydrogen cyanide, would then be able to react with each other and themselves to eventually produce the amino acids that Miller detected in the experiment (Rood and Trefil, 1981; 65)

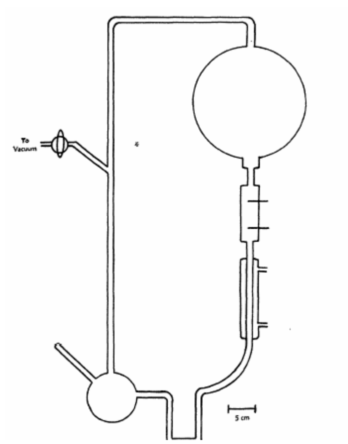

Figure 1 - Miller's apparatus (Miller, 1953)

2.2 Molecules, Not Life

Despite having created a series of amino acids, which are undoubtedly important in the creation and functioning of life, Miller's experiment was a far cry from the recreation of life on Earth. Most obviously, no life ever arose independently from the mixture of organic compounds that Miller's apparatus churned out. Additionally, and equally as important, the resultant mixture lacked any sign of nucleic acids. Deoxyribose nucleic acid and ribose nucleic acid, DNA and RNA respectively, are unequivocally necessary for the creation and survival of all living organisms currently known to exist. Without these compounds, organisms lack the ability to reproduce, synthesize proteins, or live at all. The utter lack of any nucleic acids in Miller's experiment leaves a large gap between the autonomous synthesis of amino acids from gas and the creation of life.

If not a product of Miller's experiment, what then was the first living being on Earth? Given that deoxyribose, the sugar in DNA, can be created from ribose, the sugar in RNA, it is most likely that the earliest living things contained RNA as a precursor to DNA. This RNA was capable of performing its current functions, as well as self-replicating, as was shown by Manfred Eigen, making it a suitable nucleic acid for early life. However, life needed much more than just RNA; it needed the building blocks required for self-maintenance, many of which had been synthesized in Miller's experiment. More importantly, it needed to be enclosed within a cell membrane in order to perform its functions, survive, and protect it from the outside environment (Margulis and Sagan, 1995; 83).

2.3 Synthesis of More Complex Molecules

Following Miller's experiments, John Oró began attempting to synthesize other organic compounds, using the molecules that Miller had produced. Using five molecules of hydrogen cyanide, HC≡N, Oró was able to synthesize adenine, one of the four nitrogen bases that comprise DNA and RNA (Oró and Kimball, 1966; 196). In a related synthesis, Oró was also able to create guanine, the other purine nitrogenous base (Oró and Kimball, 1966; 222). Additionally, Mariani and Torraca were later able to synthesize monosaccharides, including ribose, an important component of RNA, from the base-catalyzed condensation reactions of formaldehyde, also a byproduct of Miller's amino acid synthesis (Oró, 1965; 27). The final component of DNA and RNA, the phosphate, could also be synthesized, though through several more steps, beginning with hydrogen cyanide and an inorganic phosphate (Oró, 1965, 34). If all of these syntheses could indeed occur on prebiotic Earth, then it is reasonable to assume that the same could happen on Mars, provided that similar atmospheric and surface conditions were present. Since Mars, like Earth, has undergone extensive atmospheric and climactic changes over the approximately 4.5 billion years since its formation, it is necessary to examine its conditions both past and present.

3. Conditions on Mars

3.1 Currents Conditions

One of the most important considerations, both for the creation and maintenance of life, is liquid water. Pure liquid water at normal Earth atmospheric pressure exists between 0° Celsius and 100° Celsius. This presents a problem on present-day Mars. Like the Earth, Mars is tilted on its axis, giving it seasons, though more pronounced than Earth's due to the eccentricity of its orbit (Feinberg and Shapiro, 1980; 269). Located about 50 percent further from the Sun than Earth, at a distance of about 1.524 astronomical units versus Earth's 1.000 au (Michaux, 1967; 2), Mars consequently receives considerably less intense sunlight than the Earth, about half of that on Earth (Cattermole, 2001; 29). Additionally, because of the eccentricity of the Martian orbit, the amount of sunlight reaching the surface can vary by as much as 37 percent over the course of one revolution around the sun (Michaux, 1967; 54). The resultant mean temperature is 260 Kelvin (Michaux, 1967; 61), which corresponds to about thirteen degrees Celsius below zero. Between 1976 and 1978, the Viking Landers measured surface temperatures ranging from -90° Celsius to -10° Celsius over the course of a given day (Burgess, 1990; 42). Thus currently, the surface of Mars is too cold to support the existence of liquid water.

Equipped with the proper technology, the Viking 1 Lander was able to measure both the pressure and composition of the Martian atmosphere. The results showed that at about 95 percent, carbon dioxide was overwhelmingly the major component of the atmosphere (Cattermole, 2001; 30). If this is indeed the case, then the carbon dioxide-methane equilibrium, which Urey proposed to lie in favor of methane in the prebiotic Earth atmosphere, actually lies in the opposite direction in the current Martian atmosphere. Nitrogen is the next most abundant gas in the Martian atmosphere, at about 3 percent (Cattermole, 2001; 30). Again, this shows that the equilibrium proposed by Urey above lies in the opposite direction. Thus neither ammonia nor methane is the thermodynamically stable compound of nitrogen or carbon in the Martian atmosphere.

Besides requiring liquid water and the proper gases to satisfy the conditions for Miller's experiment to create life, an energy source is also necessary. Miller's apparatus employed an electrical discharge, which mimicked any lightning that would have been present on prebiotic Earth. However, lightning would not have been the only source of energy to catalyze the synthesis of amino acids. As Miller and Urey pointed out in 1959, many other sources of energy were available for use on the early Earth, as seen in Table 1 below (Miller and Urey, 1966; 186).

Source	Energy ($cal\ cm^{-2}\ yr^{-1}$)
Total radiation from sun	260,000
Ultraviolet light	
$\lambda < 2500$ A	570
$\lambda < 2000$ A	85
$\lambda < 1500$ A	3.5*
Electric discharges	4 †
Cosmic rays	0.0015
Radioactivity (to 1.0 km depth)	0.8‡
Volcanoes	0.13§

Table 1- Energy Sources on Earth (Miller and Urey, 1966; 186)

Many of the same energy sources would also be available for use on Mars. Although Mars receives less total radiation from the sun, it would still receive a considerable amount. Additionally, with the lack of an ozone layer presently, Mars would receive more ultraviolet light and cosmic rays. Mars also has several volcanoes, and despite the lack of knowledge surrounding its current volcanic activity, there is indeed evidence of past activity.

3.2 Past Conditions

To look at past surface conditions on Mars is somewhat more difficult, as it cannot be done directly, as a robotic probe is able to do for present conditions. Yet, through careful analysis of the present structures and features of Mars, as well as some extrapolation, it is possible to predict was the planet's surface may have been like in the past. Since the formation of the solar system, the energy output of the sun has increased by approximately 30 percent. This would tend to lead to the conclusion that Mars may have been colder than it is currently. However, the Earth itself was also subjected to the lessened solar energy, and it was just as warm, if not warmer, than it is today. Was Mars, too, considerably warmer, perhaps even warm enough for the existence of liquid water?

The fascination and attempts to find liquid water on Mars can be traced back to Giovanni Schiaparelli in the 19th century. His observations of Mars showed what he described as "canals" on the planets surface. Percival Lowell later transformed these canals into a systematic waterway designed by an advanced civilization. When the Mariner 4 spacecraft reached and photographed the surface of Mars, there was no trace of the canals, or any running water at all for that matter, on the surface of Mars. Early pictures of Mars did, however, show evidence of features that seemed to be the result of fluid seepage and surface runoff. In 1997, when the Mars Global Surveyor reached Mars and began a detailed mapping of its surface, more detailed pictures were returned. (Malin and Edgett, 2000; 2330). These features, such as the gullies seen in Figure 2, bear such a close resemblance to terrestrial formations that result from the processes of running water that they are believed to be evidence that water flowed over the surface of Mars at some point in its past. Some estimates as to the actual amount of water required to create such features are on the order of millions of cubic kilometers of water, certainly enough liquid water to be involved in a Miller-type reaction to create organic compounds (Carr, 1987; 32).

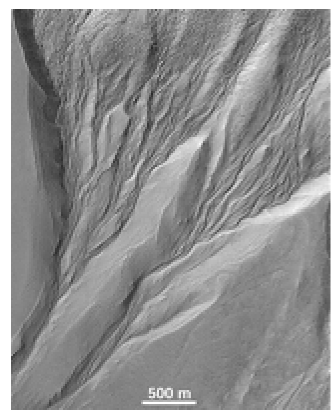

Figure 2- Gullies possibly formed by the convergence of streams on the surface of Mars (Malin and Edgett, 2000; 2333)

Discerning what the past Martian atmosphere was like is somewhat more difficult. To build from the previous argument, that water had been present on the surface of Mars at some point, the obvious conclusion is that the surface must have been significantly warmer earlier in the planet's history. An atmosphere full of greenhouse gas, such as carbon dioxide, would have allowed for more insulation, and thus warmer surface temperatures. Despite the fact that the Martian atmosphere presently is composed of approximately 95 percent carbon dioxide, the atmospheric pressure is so low that this amounts to a very tiny amount of gas. Today, the atmospheric pressure on the surface of Mars is 8 millibar, which corresponds to less than one percent of the Earth's atmospheric pressure (Cattermole, 2001; 29). If enough carbon dioxide was present in the Martian atmosphere at some point to allow for the existence of liquid water, where did it go? In the reaction seen on page 2, carbon dioxide can combine to form calcium carbonate (Cattermole, 2001; 40). This would use up, and thus deplete, the amount of carbon dioxide in the atmosphere. If this were in fact what had occurred on Mars, there would be evidence in an abundance of calcium carbonate in the Martian soil. However, neither the Viking Lander nor the Mars Pathfinder in 1997 returned any evidence of carbonates in the soil (Cattermole, 2001; 154). In an alternative view, Carl Sagan proposes that in place of carbon dioxide, the greenhouse gases actually present in Martian atmosphere may have been methane and ammonia (Sagan and Chyba, 1997; 1217). Though there remains some speculation over this hypothesis, it accounts for both the presence of greenhouse gases to warm the surface, and the lack of carbonates in the soil.

Despite the fact that the sun of the past produced less solar energy than presently, there is no reason to believe that energy on the Martian surface would be the limiting factor of whether or not the precursors to life could have been created on Mars. Even if a sufficient atmosphere had existed, the lack of an ozone layer would have still allowed for cosmic and ultraviolet radiation to reach the surface. Additionally, volcanic activity may have played a much greater role when Mars had an atmosphere than it does today.

4. Conclusions

In drawing a conclusion as to whether or not life could exist or have existed on Mars, it is important to take a moment to recap the assumptions made in this paper. First, this paper assumes that of all the possible origins of life, the manner proposed and tested by Stanley Miller was the correct one. Second, it stipulates that Miller's experiment is indeed a valid way to create amino acids and the necessary building blocks to form more complex organic molecules. Third, it is also necessary that not only are all of these processes possible and valid, but that they actually would occur if the correct conditions existed and that their execution on Earth was not merely an anomaly. Next, it would be necessary not only for the processes in Miller's experiment to occur, but for it to also be followed by such processes as proposed by Oró, since Miller clearly did not synthesize life. Finally, in looking at the conditions on the Mars surface, it would be necessary not only for all of the reactants of Miller's experiment to be present, but they would all need to be present at the same time. Clearly the probability that these conditions could all occur simultaneously is quite low. However, if, in a hypothetical situation, all of the assumptions did hold true, it would be possible to predict that life could have been created on the surface of Mars.

For life to be able to be created on Mars, three basic factors are necessary: 1) liquid water must be able to exist on the surface; 2) the atmosphere must be reducing and contain both ammonia and methane; and 3) an energy source capable of driving the subsequent reactions must be present. On present day Mars, the surface is too cold to support the existence of liquid water. What little atmosphere that does exist contains carbon dioxide, with some nitrogen, though no evidence of either methane or ammonia. Although sufficient energy sources do exist on the surface, the lack of the other necessary factors makes it impossible for present-day Mars to undergo a Miller-type creation of organic matter and thus life. This does not mean it is impossible for any life to exist on Mars presently; it merely concludes that presently life cannot be created on the Martian surface.

The Mars of the past, however, shows a different picture. Data from the various Mars probes, such as the Viking Landers, the Mars Pathfinder, and the Mars Global Surveyor, all indicate that Mars had been vastly different, even suggesting that liquid water had once been existed on the surface. One possible explanation for this liquid water is the presence of methane and ammonia in the atmosphere. Finally, that past world also possessed a sufficient energy source to catalyze the Miller-type syntheses. Provided that all of these conditions materialized simultaneously, then it is indeed possible that life could have been created on the surface of Mars at during its history.

If life was synthesized on the surface of ancient Mars, why is it no longer there today? Earlier evidence shows that the atmosphere of Mars is quite different today than in earlier periods. Perhaps, unlike like life on Earth, life on Mars was not able to survive this drastic change in atmosphere, and thus whatever caused the atmospheric alterations was also responsible for the end of life on Mars. Similar to the climatic changes thought to have killed the dinosaurs on Earth, a cataclysmic event might have been enough to wipe out any life on Mars, and all chances that life had for being created again. Since the surface of Mars shows signs of past meteorite impacts, it is not unreasonable to suspect that such an event was responsible for the destruction of early Martian life, a defeat from which life was unable to recover.

Predicting the possibility of life on Mars is only the first step. Since it is possible, even if only in a hypothetical situation, for life to have been created on Mars, it is important to continue the robotic exploration for life that the Viking missions began in the late 1970's. This would include improvements to the devices used to test for the existence of life, as well as the search for life in any location that might be feasible. It is important to continue to try and answer the questions of life on Mars, not only to better understand the planet, but also to broaden our knowledge of our own life and planet.

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