The Origin of Life and Terraforming Mars

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Abstract

The conditions for life to start and evolve have been researched thoroughly for the past few decades. New extreme conditions are being discovered to this day, which are setting the standard for scientists to search for habitability on planets other than the Earth. Also, the origin of life on Earth is of great interest to astrobiologists that are looking for signs of life on other planets. One planet is of particular significance – Mars, as it is the most Earth-like planet in the solar system. In this paper, the latest extreme conditions for life are reviewed, whether for simple or intelligent life. A history of the origin of life is also reviewed. Lastly, the environment on Mars is investigated in terms of habitability, and different ways to terraform Mars are explored.

I. Introduction

The recent conditions on Earth are known to provide a diversity of life on the planet, making it the only habitable planet known. These conditions depend mainly on some parameters put by scientists throughout the years of studying Earth, and it has faced many changes in these parameters throughout its age, which also supports the evolution of life in Darwin's vision. Consequently, if any planet or satellite has the same affordable parameters, it would probably take the same phases as Earth, and therefore, it may contain life. Studying these parameters and analyzing them is known scientifically as Exobiology.

In 1971, the Murchison meteorite was confirmed to contain amino acids, primarily glycine [1]. Since then, knowing how life started on Earth has been even more controversial in the scientific community and more questions were asked. It is estimated that life on Earth started 3.7 $\times 10^9$ years ago, almost a quarter the age of our universe. The widespread view is that life on Earth began in oceans. This view started when Charles Darwin published his book On the Origin of Species by Means of Natural Selection in 1859. However, the Murchison meteorite and similar meteorites may have new clues about the nature of life and the conditions that can support this life on planets other than Earth.

According to climate information from the National Oceanic and Atmospheric Administration (NOAA), the average of temperature trend recorded in the 21st century is 13.9 degrees Celsius. Although there is a noticeable increase of 1 degree Celsius due to the rapid climatic change, the temperature on Earth mainly depends on the Sun's and Earth's radii, the average temperature of the sun, Earth's albedo, and the distance between the Sun and Earth. Thus, any planet with the same ratio of these values is thought to have available conditions for life. An example is Gliese 667Cc [2] which is a member of the Gliese 667 triple star system, in the constellation of Scorpius which has an average surface temperature of 277 degrees Kelvin.

However, studying life on Mars specifically had gained great attention from the scientific community. Mars is the closest planet to Earth, and it has probably formed in the same conditions and time in which Earth has formed, giving it an advantage over other celestial objects. Mars has an atmosphere of 1% of Earth’s in pressure and its soil is composed of mostly silicon dioxide and ferric oxide, with a fair amount of aluminum oxide, calcium oxide, and sulfur oxide. This soil composition is relatively similar to Earth’s. Mars also has been found to contain evidence of ice and liquid water [3]. Yet it can be estimated that the discovery of Terran extremophilic microorganisms, adapted to environments previously thought to be prohibitive for life, has greatly expanded the limits of habitability in our Solar System, and has opened new avenues for the search for life on Mars. [4]

Conditions that guaranteed life on Earth will always be a continuous path of research. In this paper, all the conditions that ensured life on Earth are reviewed. This paper will also focus on similar conditions on Mars and how to terraform it.

II. The conditions for life to emerge

Many scientific fields and studies discuss the habitability and the environment on planets other than the Earth. However, to understand why a planet can even support life, one must take a step back and ask an essential question; what conditions were necessary for life to start and evolve? According to a paper by the PNAS, Life on Earth needs four general categories: energy, carbon, liquid water, and other elements [5]. These elements include nitrogen, sulfur, and phosphorus, but some organisms might use more or fewer elements, so they are not a point of interest.

i. Energy

Energy is the most critical condition for life, whether on Earth or exoplanets. For something to be considered alive, it should be able to grow, reproduce, and respond to external stimuli [6], and for these processes to occur, it requires a source of energy according to thermodynamic considerations. Nonetheless, it is not a significant concern for most planets in a planetary system. The stars in the systems produce electromagnetic radiation in the form of infrared, visible, and ultraviolet light that can be turned into energy and is enough for life to survive. For example, organisms at the Earth’s surface photosynthesize at a light level of 2000 μmol m-2 s-1. However, life can survive at much lower light levels. In a study published by the Cambridge University Press, non-oxygen marine photolithotrophs can survive at levels as low as 0.004 μmol m-2 s-1 [7]. Even Neptune, the farthest planet from the sun collecting one-thousandth of the light received by Earth, recieves light energy that is more than enough for life to form and survive. This means that scientists can shift their priorities to conditions other than energy while searching for life or habitability on other planets.

ii. Carbon

Carbon is the backbone of all living organisms on Earth and can easily link with four other atoms. This makes it the building atom of many molecules that form macromolecules such as sugars, nucleotides, fatty acids, and amino acids [8]. These molecules are the building blocks of all cell components. Sugars form polysaccharides, nucleotides build RNA and DNA, fatty acids assemble lipids, and amino acids make proteins. Carbon exists on the Earth in the form of carbon dioxide (CO2) and methane (CH4). Carbon dioxide is essential as without this gas, all ecological systems will collapse. This is because autotrophs, the energy source in any system, require carbon dioxide to complete the process of photosynthesis.

Furthermore, carbon moves between the atmosphere, the land, and the ocean, where it takes between 100 and 200 million years to do so in a process called the carbon cycle [9]. This process is crucial as it balances carbon levels and creates the greenhouse effect, which keeps the planet warm for habitability. Although carbon is necessary for life on Earth, scientists are still debating if its existence is a valuable indicator of life on exoplanets.

iii. Water

Vital processes of life all occur through chemical reactions. These reactions require a substance to break down and dissolve molecules. This substance is liquid water, which makes up 70% of a mammalian cell, and is commonly called the universal solvent [8], [10]. Water is a polar molecule that can form bonds with other molecules, including itself, making it have a unique property called cohesion. Cohesion increases the boiling point of water, which helps living organisms regulate their temperatures.

Moreover, water inside living cells creates enough pressure to oppose external forces, which keeps the structure of the cell intact. Even the shape of DNA is supported by water, allowing it to be transferred onto future cells, thus ensuring their survival and reproduction. Furthermore, cell membranes were formed because of water, as phospholipids habitually form bilayers around water. Billions of years ago, these membranes floated in oceans until they came across a hydrothermal vent, where the last universal common ancestor evolved [11]. This ancestor is the origin of all life on Earth today. This shows how important water is, as life would not have originated without it. The presence of water on exoplanets is a major indicator of habitability and signs of life, and it is the highest priority to scientists while searching for habitable planets.

iv. Environmental Conditions

Another way to look at the requirements of life is by understanding the limits of the environmental conditions in which organisms can survive. All the previous requirements discussed are fixed and will not change, at least in terms of life on Earth. However, environmental conditions are changing as researchers find new extremes for life to survive.

1) Temperature

Temperature is the most significant influence on extreme environmental conditions. In 2013, the lowest temperature for growth and reproduction was -15°C [12]. Newer research suggests that the limit is even lower at -20°C and might reach lower levels, but the consensus is that it is between -10°C and -25°C [13]. This limit is essential for planets that are present farther than the Earth in the solar system or exoplanets with cold surfaces. The upper-temperature limit depends on the cell’s domain: archaea, bacteria, and eukaryotes. Archaea achieves the highest temperature limit known for survival at 122°C [14]. Bacteria come next at a temperature limit of 100°C. However, eukaryotes, the building blocks of intelligent life, can only survive at temperatures of 40°C and 60°C [15]. This limits the search for extraterrestrial life at these temperatures, as many exoplanets discovered have high surface temperatures.

2) Radiation

As mentioned before, any star produces solar wind and radiation that is most harmful to multicellular organisms like humans. However, some types of extremophilic bacterium can survive extreme levels of radiation. For example, the Deinococcus radiodurans species of bacteria can survive 12,000 Gy of ionizing radiation [16]. To put it into perspective, 5 to 10 Gy of radiation will kill any human and most animals. Anyhow, there is no doubt that a planet’s protection from radiation is necessary for life to grow, especially intelligent species that require multicellular organisms.

3) Atmosphere

A planet’s atmosphere protects it from radiation. Nonetheless, other planets in the solar system used to have atmospheres that were stripped by solar winds, while Earth’s atmosphere is still present. This is because Earth’s magnetic field deflects the solar winds’ particles, preserving its atmosphere. Planets with atmospheres and magnetic fields are suitable for habitability as the radiation levels on them are low.

All the above conditions are what life needs to evolve on Earth. Some are necessary for any life to form outside the Earth, such as energy or water. The other conditions might or might not be exclusive to Earth only, which is under debate. Still, studying them helps to understand what conditions Mars achieves and how to improve its habitability.

III. The origin of life on Earth

With the suitable conditions available, life finally started on Earth after 0.7 billion years of its formation. Life did not come alone anyway, it came with many theories, hypotheses, and philosophies for all mankind.

Before the 1860s the origin of life was taken as a philosophical and religious concept and only exercised the minds of working scientists in a secondary manner [17]. Since the 1950s, the foundations of the modern approaches to the big question "How did life begin" have embodied research. Especially with Oparin's theory and its strong roots in biochemistry [18]. However, scientists still believe that our recent knowledge of the origin of life is a cooperation between science and philosophy. In this paper, scientific theories and explanations are given the most focus.

Generally, driven from endless theories, three main ones put a scientific explanation of how life started on Earth. The three theories explain what were the sources of the small organic molecules that made up the first self-replicating systems. Those three assumptions are: synthesis in a reducing atmosphere, input in meteorites, and synthesis of metal sulphides in deep-sea vents [19].

i. Synthesis in a reducing atmosphere

Most models of the primitive atmosphere around the time life originated suggest that the atmosphere was dominated by carbon and hydrogen-based molecules. Thus, the atmosphere was said to be reduced, meaning an absence of oxygen and similar oxidizing gases or vapours. This reducing atmosphere is estimated to be formed due to the active movement of volcanoes' eruptions, releasing significant amounts of gases composed mainly of H_2, H_2O, and CO. This reducing atmosphere has been thought to be important for prebiotic synthesis and thus the origin of life [20]. This importance started when [21] exposed a mixture of methane, ammonia, and hydrogen to an electric discharge and led the products into liquid water. Simple organic molecules and some naturally occurring amino acids were prominent among products of a considerable percentage of the carbon in the gas mixture. Miller and his team also showed that Strecker reactions, that is from aldehydes, hydrogen, potassium cyanide, and ammonia, are a major synthetic route to the amino acids.

However, this idea was not fully completed, and it was highly doubted. Recent studies such as [22] convinced that Earth at its early stage could not have probably such a strongly reducing atmosphere to obtain such reactions. That might mean that Miller's and most other early studies of prebiotic chemistry are inappropriate. Yet, the reducing atmosphere model still cannot entirely be neither accepted nor refused since Earth's early conditions are still anonymous and have a lot to be discovered.

ii. Input in meteorites

Coming to the other estimate that life was input in meteorites. As clarified in [23] the third paragraph, meteorites can bring organic matter to Earth either by their impact on the Earth's crust and reactions with the atmosphere or by direct transfer. Though direct transfer is a concept that gained scientists' attention as it depends strongly on assumptions made about the composition and density of the atmosphere, the distribution of sizes of the impacting objects, and other factors [24]. However, a high fraction of amino acids and organic matter can still be transferred through meteorites and even other celestial objects such as comets [25].

Meteorites' impacts on Earth have been importantly discussed as their role in the formation of HCN in the atmosphere. Concentrated solutions of hydrogen cyanide (HCN) can form nucleic acid bases and mixtures of HCN with carbon compounds and therefore amino acids can be produced. As shown in the study by Kurosawa [26], HCN formation in meteorite impacts may have provided a perfect mechanism for the production and concentration of cyanides. When meteorite impact events such as those of the Hadean period and larger ones were frequent, the amount of HCN created through impacts is estimated to be significant [27]. This can be the first origin sign of life particularly since other studies reveal that HCN was an important ancestor, not only for the synthesis of amino acids but for the synthesis of RNA too.

Not only might meteorites have the beginning of life in their reactions to the atmosphere, but meteorite events might also have affected the Earth’s crust and minerals. Importantly, clay formation is a ubiquitous result of meteorite impact events on Earth, being generated during the hydrothermal phase [28]. Clay in this stage might have catalysing properties that have led to the generation of RNA [29].

Back again to direct transfer meteorites. Generally, meteorites can be classified into three major groups stony, chondrites and achondrites (composed of iron), and stony-iron meteorites [30]. Carbonaceous chondrites are one of the three major classes of chondrites and they have gained a huge scientific interest due to the significant amount of organic carbon in them. This organic carbon was found to be of the standard amino acids and nucleic acid bases. In 1969 Australia, one of the most massive carbonaceous chondrites, the Murchison meteorite, was detected to have over a dozen amino acids including glycine, alanine, and glutamic acid [31]. However, that is just a small fraction of amino acids discovered in meteorites. If all meteorite classes are considered, approximately 80 amino acids have been found in total [32].

It has also been found that iron meteorites can have a big perspective on the origin of life on Earth. Studies demonstrate that iron meteorites are instantly used by iron-oxidizing bacteria as a sourceof energy [33].

iii. Synthesis of metal sulphides in deep-sea vents

The third assumption, which is the synthesis of metal sulphides in deep-sea vents, disagrees with Oparin's theory (1924) that life started with a heterotrophic origin by self-organization in a prebiotic broth. The idea is completely based on the free energy found in oceans. The theory studied by Wächtershäuser [34], [35] hypothesizes that the reaction between iron (II) sulphide and hydrogen sulphide, which yields pyrites (FeS2) and hydrogen, might reduce carbon dioxide due to the free energy combusted. This reduction might have resulted in organic molecules capable of supporting the origin of life. Later another study [36] confirmed that hydrogen sulphide, in the presence of iron (II) sulphide, will probably act as a reducing agent. Different organic molecules were reduced such as mercaptoacetic acid which was reduced to acetic acid. Nevertheless, Carbon dioxide reduction was not reported. Then again, a new study [37] demonstrated that carbon monoxide can yield from specific reduction reactions. More details about Carbon reduction can be viewed in [38]. Generally, if metal sulphides can be shown to catalyze the synthesis of an appropriate variety of organic molecules from carbon monoxide, the vent theory of the origins of bio monomers will take a new scientific path.

In this section, the three theories were briefly presented, and one might notice that they can be connected or integrated. The connections with the meteorite events input specifically have no ends and they make an interesting field of research. However, there is yet a probability that they might be all wrong and the basic molecules which build life on Earth were formed in another way. Even though, theorigin and evolution of life have long paths after the formation of organic molecules and available energy on Earth. The formation of nuclides, RNA, and other clues of life is also argued and has thousands of theories among scientists, but in this section, only the fundamentals of the origin of life on Earth are viewed. The fundamentals that may provide similar life anywhere else in the universe.

IV. Life on Mars

In the search for the most habitable planets, Mars has become a point of interest to scientists. In fact, NASA considers it the most Earth-like planet in the solar system [39]. For this reason, rovers like Opportunity, Curiosity, and Perseverance have been sent out to look for evidence of habitability, fossils, or organic compounds. Although no signs of past life have been discovered, evidence suggests Mars could have been habitable in the past [40]. This section will investigate a brief history of Mars and its present-day habitability conditions.

i. Facts of Mars

Starting with the facts, it is the second smallest planet and is the 4th from the Sun. The diameter of Earth is around half that of Mars, which means Earth's volume is 6.5 that of Mars. Although smaller, Mars has less density than Earth and 62.5% less gravity [41]. This raises problems for human missions on Mars, as microgravity causes health issues such as muscle atrophy [42]. The day cycle on Mars occurs every 24 hours and 37 minutes, which is similar to Earth's [41].

ii. The atmosphere on Mars

The major concern for habitability on Mars is the atmosphere. Its atmosphere used to support liquid water on its surface; however, the atmosphere was stripped due to solar wind from the Sun [43]. This might have occurred due to the absence of a global magnetic field that deflects solar particles. Carbon dioxide, argon, nitrogen, and water vapor are the primary components of the thin atmosphere (<1% of Earth's). It also does not provide much protection against the collision of celestial bodies on its surface. Also, the temperature on Mars ranges from -153°C to 20°C [44]. Radiation is currently the biggest concern for the habitability of Mars, as the radiation dosage per year on Mars is around 40 times higher than the Earth [45].

iii. Water on Mars

The most important characteristic of Mars that has led scientists to investigate it is the presence of water on its surface in the past. Billions of years ago, Mars is thought to have had a denser atmosphere with a higher carbon dioxide pressure of between 100 and 500 kilopascals, compared to its present-day pressure of 0.6 kilopascals [46], [47]. Also, its surface temperature was estimated to be higher, which assisted in forming liquid water on the surface [46], [48]. Research also suggests that Mars might have been covered by a northern hemispheric ocean, which took up one-third of its surface [49].

1) Gale Crater

Even at the present, geologic evidence points to the presence of ancient water on Mars. One example of this would be Gale Crater. This crater was the landing spot of the Curiosity rover that NASA deployed in 2012 at the Aeolis Palus plain, as shown in figure 1. The crater was formed after an asteroid hit Mars billions of years ago [50]. The Curiosity rover found sedimentary rocks indicating the presence of an ancient lake with neutral acidity and low salinity.

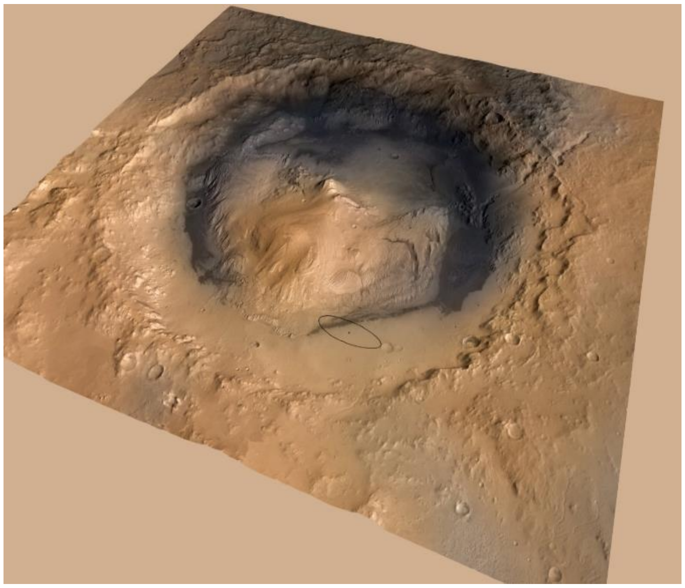

Figure 1: Image depicts Gale Crater on Mars, computed by elevation and color data. The elliptical mark shows the landing area of the Curiosity rover in Aeolin Palus. Credit: NASA/JPL-Caltech/ESA/DLR/FU Berlin/MSSS

Furthermore, important biological elements were discovered while analyzing samples drilled by the rover include carbon, oxygen, and hydrogen. All this evidence supports that the crater had a habitable environment for life [51]. However, the current environment is dry and inhabitable. To this day, the Curiosity rover is still investigating the crater for past life and other studies that plan human exploration in the future [52].

2) Eberswalde Delta

Another compelling piece of evidence for water on Mars is at the Eberswalde crater. In the Perseverance rover mission, the crater was on the list of landing sites for the mission. Although the rover landed in another place, the crater is still on the list for future missions. Nonetheless, what is most interesting about the crater is the presence of the 115 km^2 Eberswalde Delta, as shown in figure 2. To recognize how significant the discovery of a delta on the surface of Mars is, one needs to understand how deltas form.

Essentially, a delta is formed after a long period of time when a river empties their water to another body of water [53]. For a point of reference, theMississippi river delta formed after around 11,000 years [54]. This means that for the Eberswalde Deltato form, it required deep river water around it for possibly thousands of years, indicating a habitable environment for life in the past. Furthermore, evidence suggests that the delta had high sediment deposition rates, making it easier to find preserved biosignatures for life [55].

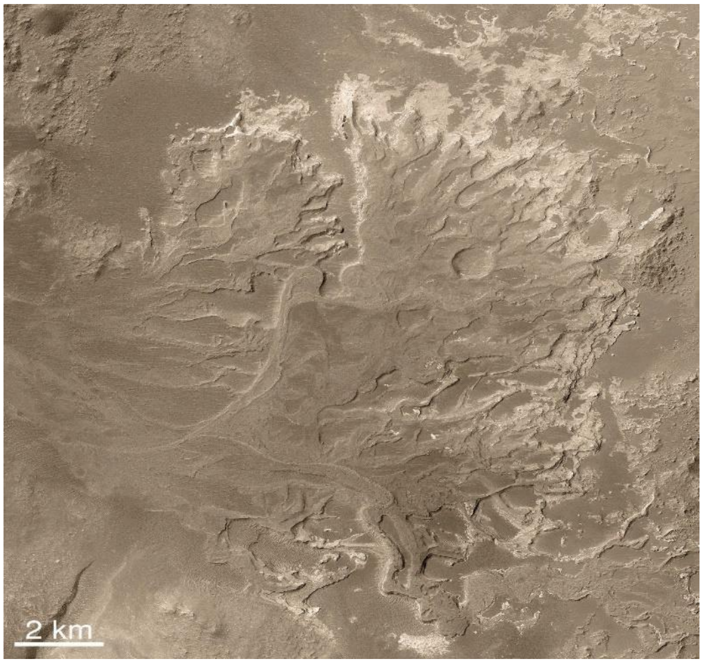

Figure 2: Image pictures Eberswalde Delta in the Eberswalde crater of Mars. It was captured by NASA's Mars Orbiter Camera and released to the public in 2003. Credit: NASA/JPL/MSSS.

3) Martian Polar Ice Caps

Lastly, water on Mars is not a thing of the past. Although not liquid, there exist two polar ice caps of ice water. One at the north called Planum Boreum, and one at the south called Planum Australe (figure 3). During winter, either pole is exposed to cold surface temperatures, which causes the carbon dioxide gas in the atmosphere to solidify and accumulate on the poles. The thickness of the dry ice layer when it accumulates is around one meter on either pole [56]. In 2018, research suggested that radar measured signals of a liquid lake water underneath the surface of the southern ice cap, which broke the record as the first to be found on Mars [57]. Although researchers are divided about the authenticity of the signals received, it is still a major step for finding liquid water on the planet and, in turn, signs of past life.

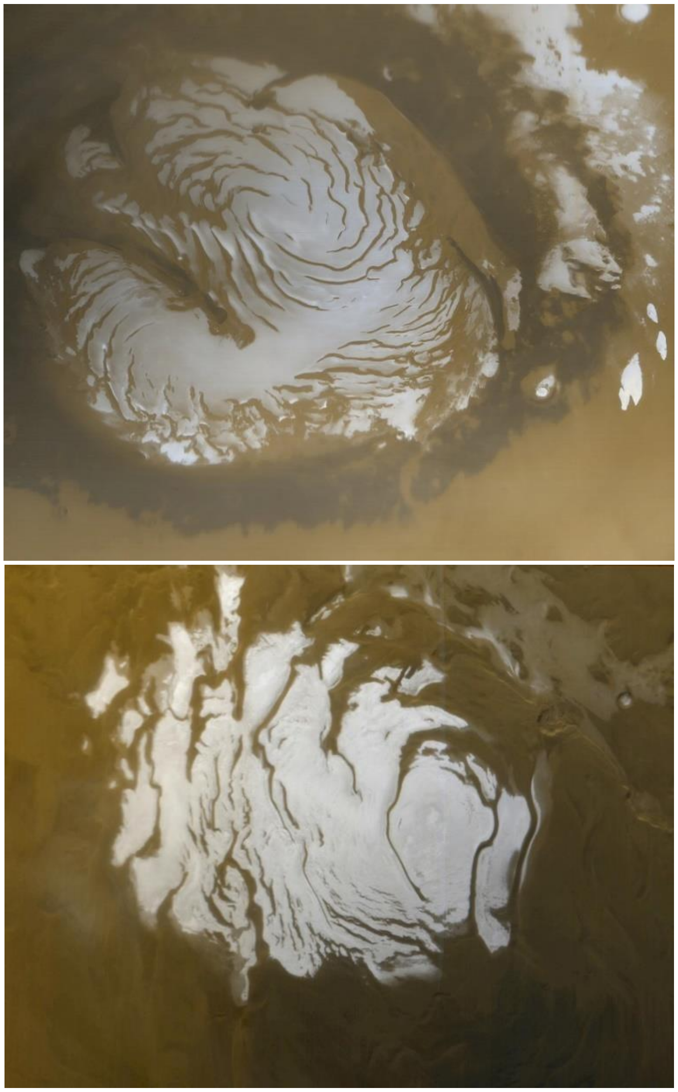

Figure 3: The image at the top pictures the north polar ice cap (Planum Boreum) in the year 1999, while the bottom one pictures the south polar ice cap (Planum Australe) in the year 2000. They were both captured by NASA's Mars Orbiter Camera. Credit: NASA/JPL/MSSS.

V. Terraforming Mars

Terraforming is defined as the process of global environmental engineering to make a large area (e.g., outer space planets) habitable. The curiosity of mankind has always planned to utilize this process throughout the ages. The first Martian terraforming models to be published in the technical literature were by Bums and Harwit (1973) [58] and Sagan (1973) [59]. Terraforming Mars is yet taking new paths, proving the reality of the process away from science fiction.

i. Modifications to terraform mars

For Mars to be terraformed, there must be suitable conditions to make biota life possible (See the previous sections). For humans and other creatures to terraform, the process must occur in stages. Ecopoiestis, or the earliest biological stage in a terraforming process which is essential for all other stages [60], inappropriately, cannot take place spontaneously. Therefore, no known living creatures are expected to thrive long on the Martian surface. In order to allow ecopoiesis, four principal modifications must be applied to the Martian environment as estimated by [61]: the average global surface temperature must be increased by 60 K; the mass of the atmosphere must be increased; liquid water must be ensured available, and the surface UV and cosmic ray flux must be significantly reduced.

These four modifications might make life possible for some anaerobic species. With the current experiments and changes on the Martian surface Terran extremophilic microorganisms and other prokaryotes were estimated to survive on it [62][63]. However, that is not the same case with plants. Although they consume much less oxygen than animals, plants' need for oxygen is not recently available on Mars [64]. Thus, the fifth modification of making mars providable for sufficient oxygen is added to the previous four.

As presented in [65], solving the challenge of low Martian atmospheric pressure, and therefore its mass, has gained the most focus. It was expected that solving this issue is the key to solving the others as they are all interlinked. For instance, higher atmospheric pressure will cause molecules to be more tide together so a meteor and radiation shield will be formed, which will improve the greenhouse effect, and hence the average temperature will rise, and finally, as a result, liquid water will be more stably and extendedly found on the surface. In other words, it will undergo the same stages that formed the Earth as known now. Shreds of evidence on Mars suggest that it probably had a thicker and more massive atmosphere in the past composed mainly of carbon dioxide [66]. Over millions of years, Sun's pressure attracted the molecules in the Martian atmosphere causing it to become more loosely.

ii. Previous trials and plans to terraform Mars

Many studies are focused on methods of providing a denser thicker Martian atmosphere back again. The use of orbiting mirrors to reflect the light that passes a planet down to its surface and accordingly increases the solar energy input and warm up the planet was wide suggested in the Martian situation [61][65]. The production of such mirrors will require an enormous mass and size, which may be an obstacle to this idea [67]. Other ideas were involving the addition of specific greenhouse gasses to the Martian atmosphere. Studies [68] [69] on CFCs in Mars' atmosphere demonstrated that CFCs on Mars is not as stable and long-lasting as on
Earth. That's mainly because UV radiation, which breaks the C-Cl bond, is not shielded from the surface by an ozone layer. Also, the time of residence for a typical CFC molecule turned to be only hours, compared with the regular residence onEarth that can last days or even months.
Consequently, it is doubted about its total efficiency. Yet using perfluoro compounds instead of the C-F ones are thought to be much more vigorous [70]. Perfluorocarbons are so inert they can survive conditions on Mars but most of their relevant absorption bands, though there are still estimated issues evolved in their reactions.

In this section, brief information about the experiments, trials, challenges, and goals to terraform Mars was indicated. Although most studies estimate that humans cannot effectively terraform Mars before roughly 20 years up to the date these words were written [65], continuous scientific research and experiments will always be done to terraform Mars.

VI. Conclusion

Life needs energy, carbon, liquid water, and a suitable environment. Energy is abundant from any star in a planetary system. Carbon is an essential element for life, but scientists are debating its importance on exoplanets. Liquid water is the most important for life and habitability. As for environmental conditions, life needs suitable temperatures, an atmosphere for air pressure and protection against radiation, and a magnetic field to protect the atmosphere from solar winds.

Furthermore, three main theories explain the origin of life. The first one is the synthesis of prebiotic compounds in a reducing atmosphere. The second assumption is that organic matter was brought to Earth by meteorites either by reactions with the atmosphere or direct transfer. The last theory is the synthesis of metal-sulphides in deep-sea vents that supported life. Although all of them are debated for their accuracy, they still develop a solid foundation for how life started and how it can start other planets like Mars.

Moreover, the evidence for ancient water on Mars like at Gale Crater or Eberswalde Delta supports the hypothesis that Mars was habitable in the past and life could have evolved on it. The radar evidence for liquid water today on Mars also increases the probability of past life on it. Future research should investigate biosignatures on the southern Martian ice cap, and it should be a candidate for NASA's future Mars exploration.

Lastly, the terraforming of Mars is a point of interest to scientists as it is the most Earth-like planet. The most crucial step for a successful terraforming is providing a thicker atmosphere, which will solve other issues that are linked with a thin atmosphere. Many research methods were proposed that include the usage of orbiting mirrors or greenhouse gases. However, the methods still face some roadblocks. It is estimated that humans need at least 20 years to terraform the planet. In the meantime, research and experimentation should continue until effective ways are found to terraform Mars.

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