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INVITED REVIEW

Origin of Life

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Abstract The evolution of life has been a big enigma despite rapid advancements in the field of astrobiology, microbiology and genetics in recent years. The answer to this puzzle is as mindboggling as the riddle relating to evolution of the universe itself. Despite the fact that panspermia has gained considerable support as a viable explanation for origin of life on the earth and elsewhere in the universe, the issue, however, remains far from a tangible solution. This paper examines the various prevailing hypotheses regarding origin of life-like abiogenesis, RNA world, iron–sulphur world and panspermia, and concludes that delivery of life-bearing organic molecules by the comets in the early epoch of the earth alone possibly was not responsible for kick-starting the process of evolution of life on our planet.

Keywords Abiogenesis · Panspermia · LUCA · Microbes · Thermophiles · Extremophiles · Cyanobacteria · DNA · RNA · RNA world · Iron–sulphur world · Miller–Urey experiment · Comets

1 Introduction

The question of the evolution of life on the earth and elsewhere in the universe has ever been as challenging as the question of evolution of the universe itself. Science does not provide authentic explanation regarding the origin of the universe in the controversial "Big Bang" (Arp et al. 1990) theory for evolution of the universe, nor does it provide any satisfactory explanation regarding the origin of life despite considerable advancements in the fields of astrobiology, genetics and microbiology in recent years. The "Big Bang" model for evolution of the universe is not secure enough to serve as a foundation for beliefs about the origin of life, which is exemplified very much by the fact that the most distant galaxies we can see today look as rich and fully evolved as our own, even though they are theoretically only 5% as old as revealed in the Hubble Ultra Deep Field (HUDF) images taken with Hubble's advance camera for surveys and near infrared camera. Among the several factors leading to beginning of life on this planet, "panspermia" appears to provide the most favoured hypothesis for emergence of life on our planet. This paper examines the various prevailing hypotheses regarding origin of life on this planet. It also hints at a very interesting and crucial inference that probably delivery of life-bearing organic molecules by the comets in the early history of earth alone was not sufficient to provide the requisite trigger mechanism for initiation of life on our planet.

2 Early earth and beginning of life

Earth formed as part of the birth of the solar system about 4.6 billion years ago. It was then very different from the world known today (Rollinson 2006; Ehrenfreund et al. 2002). There were no oceans and oxygen in the atmosphere. During the period 4.3–3.8 billion years ago (the Hadean Epoch), it is believed to have undergone a period of heavy meteoric bombardment for about 700 million years. It was bombarded by planetoids and other material leftovers from the formation of the solar system. This bombardment, combined with heat from the radioactive breakdown, residual heat, and heat from the pressure of contraction caused the

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planet at this stage to be fully molten. Heavier elements sank to the center while the lighter ones rose to the surface producing earth's various layers. The early earth was lifeless and simply inhospitable with its atmosphere dominated by the surrounding materials from the solar nebula, especially light gases such as hydrogen and helium. The planet is believed to have cooled quickly with formation of solid crust within 150 million years, and formation of clouds in about 200 million years. The subsequent rains gave rise to the oceans within 750 million years of earth's formation, making it a habitable planet for the first time in its history. It may not be out of place to mention here that liquid water is the most essential ingredient to trigger the beginning of life. Water provides an excellent environment for the formation of complicated carbon-based molecules that could eventually lead to the emergence of life. Steam escaped from the crust while more gases were released by volcanoes, creating the second atmosphere in earth's early history. Life on earth may have emerged during or shortly after the early heavy bombardment phase, perhaps as early as 3.90–3.85 billion years ago, but the precise timing remains uncertain. A prebiotic reducing atmosphere, if present, predicts that building blocks of biopolymers—such as amino acids, sugars, purines, and pyrimidines would be formed in abundance (Ehrenfreund et al. 2002). Recent modeling of the earth's early atmosphere, however, suggests that the new atmosphere probably contained ammonia, methane, water vapor, carbon dioxide, nitrogen, and a trace of other gases. It is generally believed that until 2.4 billion years ago, the earth's atmosphere was generally devoid of oxygen. Volcanic activity was intense and without an ozone layer to hinder its entry, ultraviolet radiation flooded the surface. Thus, the early earth was just one big chemical evolution experiment (Rollinson 2006). Many scientists now believe that dust particles from comets and meteriorites—rich in organic compounds, rained down on early earth which are believed to have provided an important source of molecules that gave rise to our life on our planet.

As per the conventional hypothesis, the earliest living cells emerged as a result of chemical evolution on our planet billions of years ago in a process called "abiogenesis" connoting generation of life from nonliving matter. The term is primarily used to refer to theories about the chemical origin of life, such as from a primordial sea, and most probably through a number of intermediate steps, such as nonliving but self-replicating (biopoiesis). The first indications of life on the earth come from fossils and carbon inclusion in rocks. The western Australian greenstones, together with similar rocks from Greenland and South Africa are some of the oldest rocks on the earth. As per the palaeontogical findings relating to the beginning of life on earth, "stromatolites," the oldest microfossils (dome-shaped clumps of bacteria) relating to 11 species of bacteria found in the archaean rocks from western Australia date back to around 3.5 billion years (Schopf et al. 2002). They are colonial structures formed by photosynthesizing "cyanobacteria" (blue-green algae) and other unicellular microbes, and are believed to be the "last universal common ancestor" (LUCA). Cyanobacteria produced oxygen as a by-product of photosynthesis, like today's plants, and played a vital role in the history of our planet. This "LUCA cell" is the ancestor of all cells, and hence all life on earth. Even older rocks from Greenland, believed to be more than 3.8 billion years old, contain isotopic fingerprints of carbon that could have belonged only to a living being.

In a 1996 paper published in *Nature*, Mojzsis and his-coworkers had reported controversial evidence of ancient life dating back to some 3.86 billion years ago found in a rock formation on Akilia Island in west Greenland (Mojzsis et al. 1996). Scientists look for evidence of life in ancient rocks like those from Akilia Island by searching for chemical signatures and isotopic evidence. The carbon isotope change on the Akilia Island rock sample, analyzed with high-resolution microprobe, gave an indication of emergence of life on earth at least 3.86 billion years ago. This was at the end of the period of heavy bombardment of the earth by comets and meteorites. The researchers found that the ratio of carbon-12 to carbon-13 was 3% higher than would be expected if life were not present. Since living organisms use the lighter carbon-12, rather than the heavier carbon-13, a lump of carbon that has been processed by a living organism has more carbon-12 atoms than one found in other places in nature. Recently, Manning et al. (2006) at the UCLA Department of Earth and Space Sciences have mapped an area on the Akilia Island where ancient rocks were earlier discovered by Mojzsis and his teammates to preserve carbon-isotope evidence for life at the time of their formation. Their findings, as reported in the *American Journal of Science*, lend credibility to the fact that these rocks are 3.86 billion years old and contain traces of ancient life (Penny and Poole 1999). At the time of the 1996 *Nature* paper, there was no reliable map showing the geology of the area.

The earliest form of life was a prokaryote, unicellular bacteria possessing a cell membrane and probably a ribosome, but lacking a nucleus or membrane-bound organelles such as mitochondria or chloroplasts that thrived in aquatic environments, and ruled the earth in its early history (3 billion to 1.5 billion years ago). Like all modern cells, it used DNA as its genetic code, RNA for information transfer and protein synthesis, and enzymes for catalyzing reactions (Penny and Poole 1999). For a long time in the history of earth, the land remained barren of eukaryotes—complex multicellular organisms comprising plants and animals including us humans. Eukaryotic cells developed about 1.5 billion years ago in a stable environment rich in oxygen. The oldest fossils of land fungi and plants date to 480 million to 460 million years ago, though molecular evidence suggests the fungi may have colonized the land as early as

1 billion years ago, and the plants 700 million years ago (Heckman et al. 2001). Anatomically, modern humans—Homo Sapiens are believed to have originated somewhere around 200,000 years ago or earlier; the oldest fossil dates back to around 160,000 years ago (Gibbons 2003).

3 Spontaneous generation

Darwin was the first to advocate that "life could have arisen through chemistry in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc. present." For much of the twentieth century, origin of life research centered around Darwin's hypothesis—to elucidate how, without supernatural intervention, spontaneous interaction of the relatively simple molecules dissolved in the lakes or ocean of the prebiotic world could have yielded life's last common ancestor. In 1920s, Oparin in Russia and in Haldane in England revived ideas of spontaneous generation suggesting that the presence of atmospheric oxygen prevented a chain of events that would lead to the evolution of life. As early as 1929, Haldane (1947) had drawn attention to experiments in which ultraviolet radiation had been seen to encourage the build-up of organic compounds from a mixture of water, carbon dioxide, and ammonia. Oparin (1938) argued that a "primeval soup" of organic molecules could be created in an oxygen-less atmosphere, through the action of sunlight. Oparin and Haldane thus proposed that the atmosphere of the young earth, like that of outer (Jovian) planets, was deprived of oxygen or contained very little oxygen (O_2), and was rich in hydrogen (H_2) and other chemical compounds such as methane (CH_4) and ammonia (NH_3).

Inspired by the ideas of Darwin, Oparin, and Haldane, the duo of Miller and Urey performed experiments in 1953 (Fig. 1) under simulated conditions resembling those then thought to have existed shortly after the earth first accreted from the primordial solar nebula, thus heralding the era of experimental prebiotic (nonliving) chemistry (Miller 1953; Urey 1952). Their experiments demonstrated that amino acids and other molecules important to life could be generated from simple compounds assumed to have been present on the primitive earth. In a self-contained apparatus, Miller and Urey created a reducing atmosphere (devoid of oxygen) that consisted of water vapor, methane, ammonia, and hydrogen above a "mock ocean" of water. For this, they set up a flask of water to represent the ocean, connected to another flask of gases through which they passed an electrical discharge to represent lightning. After just 2 days, they analyzed the contents of the "mock ocean." Miller observed that as much as 10–15% of carbon in the system was converted into a relatively small number of identifiable organic compounds, and up to 2% of carbon went into making amino acids of the kinds that serve as constituents of proteins. This last discovery was particularly exciting as it suggested that the amino acids—the basic building components of life would have been abundant on the primitive planet. "Glycine" was the most abundant amino acid resulting from this experiment and similar experiments conducted subsequently. A surprising number of the standard 20 amino acids (proteins that form the basic building block of life) as well as other molecules like purines and pyrimidines associated with living cells were also made in this experiment. The experiment showed that some of the basic organic monomers (such as amino acids) which form the polymeric building blocks of a modern life can be formed spontaneously. Ironically, simple organic molecules are always a long way from becoming a fully functional self-replicating life-form. Moreover, spontaneous formation of complex polymers from abiotically generated monomers under the conditions presumed in Miller's experiments is not at all straightforward process.

4 RNA world

Biologists, by and large, agree that bacterial cells cannot form from nonliving chemicals in one step. If life arises from nonliving chemicals, it is speculated there must be some intermediate form of "precellular life." Of the various theories of precellular life, in the early stages of evolution of life on earth, the most popular contender today is the "RNA world" hypothesis (Gilbert 1986; Orgel and Crick 1968; Maddox 1994), It encompasses polymerization of nucleotides into random RNA molecules that might have resulted in self-replicating ribozymes (enzyme). RNA (ribonucleic acid) is a nucleic acid consisting of nucleotide monomers that act as a messenger between DNA (deoxyribonucleic acid) (Fig. 2), which is present in all living organisms as the carrier of genetic information, and ribosomes which are responsible for making proteins out of amino acids. Single rather than double-stranded, RNA is a nucleic acid—a chip from original DNA, first hypothesized in late 1950s to act as the first in a chain of intermediates leading from DNA to protein (DNA > RNA > Protein).

In 1968, Orgel and Crick (1968) had suggested that RNA must have been the first genetic molecule. According to them, evolution based on RNA replication preceded the appearance of protein hypothesis. They also held the view that RNA, besides acting as a template, might also act as an enzyme (catalyst), and in so doing, catalyze its own self-replication. Because it can replicate on its own, performing the task of both—DNA and protein, RNA is believed to have been capable of initiating life on its own in the early history of earth. In the early stages of life's evolution, all the enzymes may have been RNAs, not proteins. The precise event leading to the RNA world however, remains unclear so

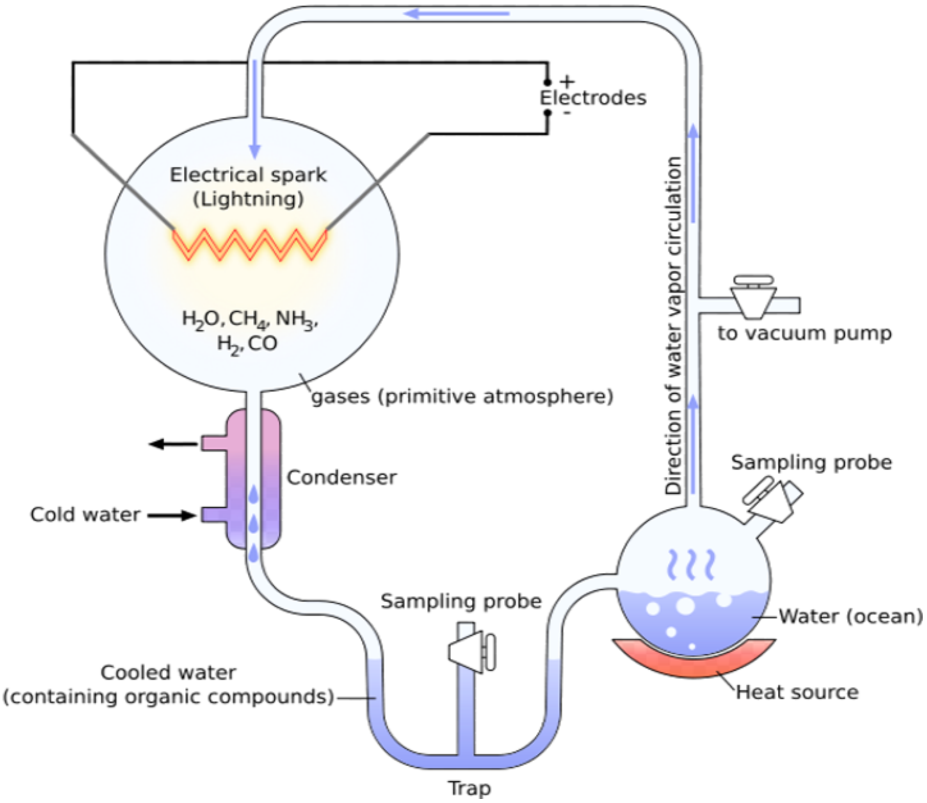

Fig. 1 Miller–Urey experiment. Credit: http://en.wikipedia.org/wiki/Miller–Urey_experiment

far. The self-replicating RNA molecules were believed to be common 3.6 billion years ago though the interval in which the biosphere could have been dominated by RNA-based life forms is believed to be less than 100 million years.

A few biologists like Senapathy, however, insist that DNA could initiate life on its own (Senapathy 1994). But even the shortest DNA strand needs protein to help it replicate. This is the "chicken and egg" problem (genes require enzymes; enzymes require genes). Which came first, the chicken or egg? DNA holds the recipe for protein construction. Yet that information cannot be retrieved or copied without the assistance of proteins. Which large molecule then appeared first in getting life kick started—proteins (the chicken) or DNA (the egg)? A simple solution to the "chicken-and-egg" riddle, according to Gilbert is: "one can contemplate an RNA world, containing RNA molecules that serve to catalyze the synthesis of themselves, and the first step of evolution proceeds then by RNA molecules performing the catalytic activities necessary to assemble themselves from a nucleotide soup" (Gilbert 1986). In his vision, the first self-replicating RNA that emerged from nonliving matter carried out functions now executed by RNA, DNA, and proteins. A number of additional clues seemed to support the idea that RNA appeared before proteins and DNA in the evolution of life. Many small molecules called "cofactors," play an important role in enzyme-catalyzed reactions. These cofactors often carry an attached RNA nucleotide with no obvious functions. These structures have been designated as "molecular fossils," relics descended from the time when RNA alone, without DNA or proteins, ruled the biochemical world. However, the million dollar question is: How did the first self-replicating RNA arise? In addition, chemists have been able to synthesize new ribozymes that display a variety of enzyme-like activities (Shapiro 2007).

Another interesting idea is the "PNA" world proposed by Stanley Miller and Oragel. Since starting the RNA world is so difficult, there probably needs to be a pre-RNA world. PNA (peptide nucleic acid) was hypotherized to be the first prebiotic system capable of self-replication on early earth (Bohler et al. 1995). It was presumed that the earliest life on the earth may have used PNA as a genetic material due to its extreme robustness, simpler formation and possible spontaneous polymerization at normal boiling temperature (Wittung et al. 1994). PNA was believed to have bases bound to a peptide-like backbone, in contrast to the sugar-phosphate backbone of RNA. This would be precellular life. Ironically, there is no remnant or trace evidence available of the precellular life (PNA) anywhere today. Its existence is deemed to be entirely conjectural, nor has any precellular life ever been created in a laboratory. Even if the precellular life is presumed to exist in the early epoch of the earth's existence, there is a problem getting from there to proteins, genes, and cells. The random production of protein does not succeed as an explanation. Although its emergence from nonliving

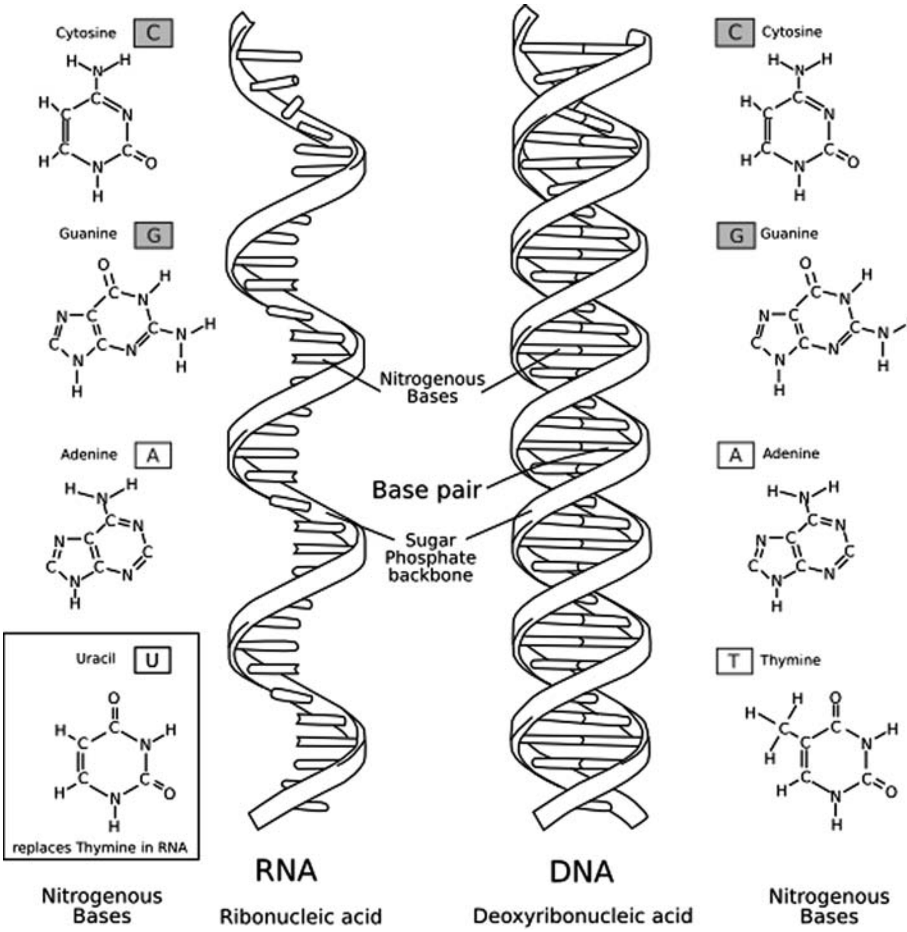

Fig. 2 RNA with nitrogenous bases to the *left* and DNA to the *right*. Credit: http://en.wikipedia.org/wiki/RNA_world_hypothesis

matter is hard to conceive, precellular life is believed to have appeared almost spontaneously. Even here, science remains clueless about the timing of spontaneous infusion of life into precellular entity. Researchers are also unclear how even some of the shortest amino acid chains, called peptides formed prior to the dawn of the living organisms.

Although Joyce (2002) recognizes "RNA world" as the leading account of the origin of life from nonlife, he also acknowledges many of the problems inherent in the "RNA world" hypothesis. The foremost obstacle to understanding the origin of RNA-based life is identifying a plausible mechanism for overcoming the clutter wrought by prebiotic chemistry. Other notable problems with the hypothesis relate to the instability of RNA when exposed to ultraviolet light, the difficulty of activating and ligating nucleotides, and lack of available phosphate in solution required to constitute the backbone, and the instability of the base cytosine which is prone to hydrolysis. RNA is chemically fragile and difficult to synthesize abiotically. The known range of its catalytic activities is rather narrow, and the origin of an RNA synthesis apparatus is unclear. To solve some of these problems, Joyce suggests, "some other genetic system proceeded RNA, just as it preceded DNA and protein." He further adds that RNA-based functions for which there is no evidence in biology, such as nucleotide synthesis and RNA polymerization are assumed to have existed in the RNA world on first principles. Ironically, the assumption is not supported by available historical evidence.

5 Extremophiles

Extremophiles (Mondigan and Marrs 1997; Fredrickson and Onstott 1996; Brock 1978). are usually unicellular microbes (bacteria and archaea) that can survive in the harshest environment on the planet—considered extremely inhospitable for habitation by humans and other creatures. Many of them are evolutionary relics called "archaea," believed to be among the first homesteaders on the earth 3.8 billion years ago. They are presumably the first version of life on our planet when its atmosphere was devoid of oxygen, and comprised largely of ammonia, methane, water vapor, and carbon dioxide. They are microorganisms similar to bacteria in size and simplicity of structure, but continue as an ancient group intermediate between bacteria and eukaryotes. Heat-loving microbes or "thermophiles," are among the best studied of the extremophiles that can reproduce or grow readily in temperatures exceeding 45°C, and some of them, referred to as "hyperthermophiles," are capable of thriving even in temperatures as high as 110°C—more than the temperature of boiling water. These microbes are known to have colonized a variety of extremely hot places such as hot springs, deep oceanic vents, and the deep subsurface. In New Zealand microbes have been found to flourish in pools of temperature up to 101°C (Postgate 1994). In the hot, acidic springs of Yellowstone National Park (USA), microbes have been found to be thriving in temperatures of up to 95°C. Since these discoveries, subsequent explorations to various hot springs and deep sea hydrothermal vents have led to identification of more than 50 species of "hyperthermophile." The most heat-resistant of these microbes, "pyrolobus fumari" found near the walls of black smokers (hydrothermal vents) on the ocean floor thrive at temperatures of 105°C, and have been found to reproduce in temperatures of up to 113°C (Postgate 1994). The majority of the hyperthermophiles found near the black chimneys (vents) are anaerobes that do not require any oxygen for their survival. Hyperthermophiles (Brock 1978) living in and around the dark hydrothermal vents along the mid-oceanic ridges harness chemical energy from hydrogen sulphide (H_2S) and other molecules that billow out of the sea floor at temperatures as high as 121°C.

The ability of life to tap such geothermal energy raises interesting possibilities for other worlds like Jupiter's moon, Europa, which probably harbors liquid water beneath its icy surfaces (Is there life on Europa? 2004). Europa is squeezed and stretched by gravitational forces from Jupiter and other Galilean satellites. Tidal friction heats the interior of Europa possibly enough to maintain the solar system's biggest ocean. It is guessed that similar hydrothermal vents in Europa's dark sea fuel ecosystems like those found on earth. Based on these speculations, existence of water oceans even on other moons in the solar system like Jupiter's other satellites—Callisto and Ganymede, Enceladus (Saturn's moon), and Triton (Neptune's moon) with the possibility of life thriving within their interiors cannot be ruled out. Radar observations made by the Cassini spacecraft regarding Titan's rotation and shifts in the location of surface features are suggestive of a vast ocean of water and ammonia lurking deep beneath its surface (Lorenz 2008). Microbes (methane-oxidizing archaea) found thriving at a record depth of 1.62 km beneath the Atlantic sea-bed at a simmering temperature range of 60–100°C gives rise to the possibility that life might evolve under similar conditions on other planets and their satellites as well (Roussel 2008). The living prokaryotic cells in the searing hot marine sediments ranged in age from 46–111 million years.

Some thermophiles live in remarkable depths within the earth's crust. In South Africa, samples of rock from gold mines more than 2.8 km below the surface show the presence of thriving thermophiles that derive all its energy from the decay of radioactive rocks rather than from sunlight (Lin et al. 2006). The self-sustaining bacterial community represents the first group of microbes known to depend exclusively on geologically produced hydrogen and sulphur compounds for nourishment, and lives in conditions similar to those of early earth. The subterranean world, according to Lin and his colleagues, whose findings were reported in a 2006 issue of *Science*, is a lightless pool of hot and pressurized saltwater which stinks of sulphur and noxious gases that humans would find unbearable. The microbes discovered in the South African mine are related to the "firmicutes" division of microbes that exist near the hydrothermal vents and appear to have survived for tens of million of years without any nutrients derived through photosynthesis. The bacteria's rocky living space is a metamorphosed basalt that is 2.7 billion years old. How the surface-related "firmicutes" managed to colonize in an area so deep within earth's crust is a mystery. Some surface "firmicutes" are known to consume sulphate and hydrogen as a way to get energy for growth. As per the DNA analysis of the bacterial genes, the subsurface "firmicutes" were removed from contact with their surface cousin anywhere from 3 to 25 million years ago (Lin et al. 2006). The extreme conditions under which the bacteria live bear a resemblance to those of early earth, potentially offering insight into the nature of organisms that lived long before our planet had an oxygen atmosphere.

6 Thermophiles and deep-sea-origin of life

Hyperthermophiles (Brock 1978), having the capability to thrive at temperatures between 80–121°C, such as those found in hydrothermal systems, are deemed to be our closet link to the very first organisms to have evolved on the earth. At the beginning of life, the earth was a hotter planet due to the increased greenhouse effect of a carbon dioxide (CO_2)-rich atmosphere. This early atmosphere also did not contain oxygen until the "great oxidation event" 2.3–2.4 billion years ago. Because life started at least 3.5 billion years ago, it was exclusively anaerobic for at least 1.5 billion years. Unique heat resistance and anaerobic nature of many hyperthermophiles could be the traits of the earliest organisms on the earth as well. Astrobiologists are increasingly becoming convinced that life on earth itself might have started in the sulfurous cauldron around hydrothermal vents. Indeed, many of the primordial molecules needed to jumpstart life could have been found in the subsurface out of the interaction of rock and the circulating hot water driven by the hydrothermal systems. Even the "iron-sulfur world" first hypothesized by Wächtershäuser (Huber and Wachtershanser 1998) in 1980s, identifies the "last universal common ancestor (LUCA)" inside a black smoker (Figs. 3 and 4) at the ocean floor, rather than assuming free-living form of LUCA.

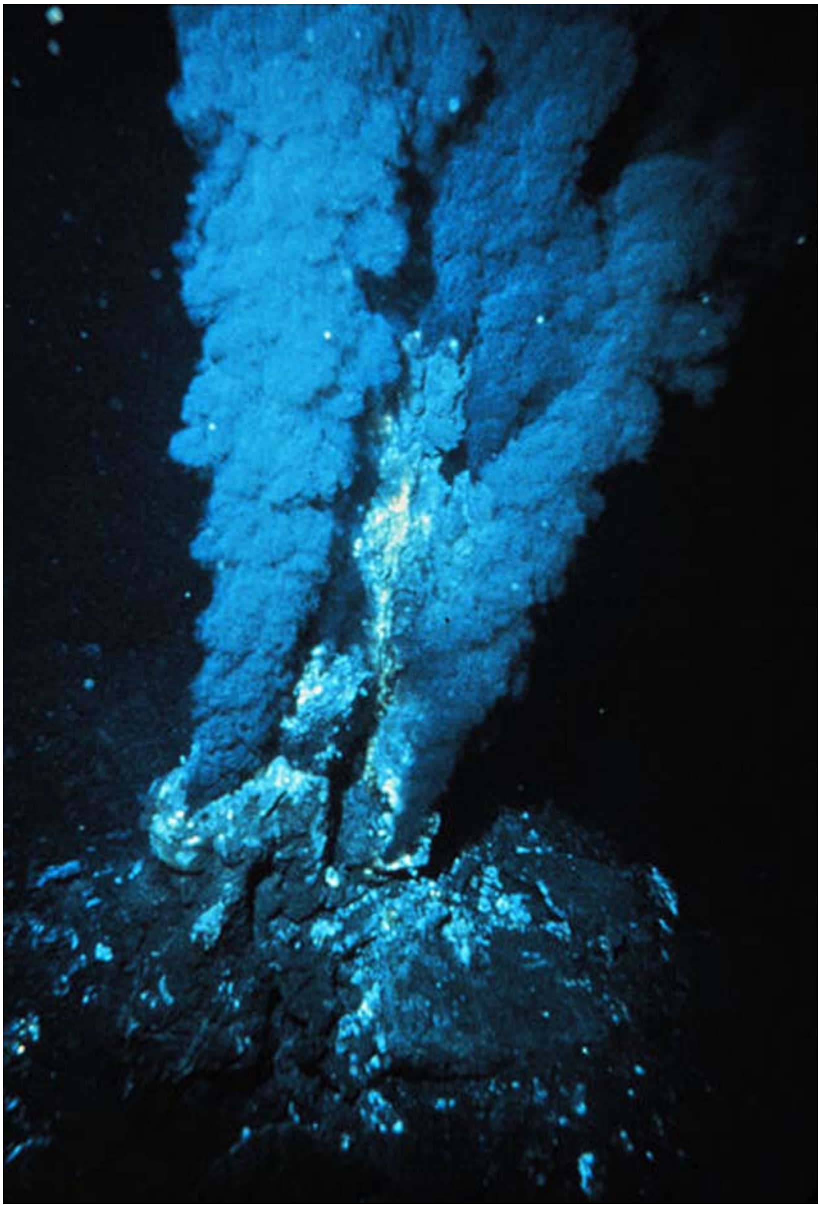

Fig. 3 Black smoker at mid-ocean ridge hydrothermal vent in the Atlantic Ocean. Credit: http://www.photolib.noaa.gov/htmls/nur04506.htm

The discovery of an entire ecosystem inside a black smoker, 2,000 m below the ocean surface first discovered in 1977 using an US submarine, that did not survive on photosynthesis for survival, provided ground for scientists to have a relook at the existing notion about origin of life (Shorpe and Pickrell 2006). A hydrothermal vent is a fissure in a planet's surface from which geothermally heated water emerges. Such vents are commonly found near volcanically active places, areas where tectonic plates are moving apart, and new crust is being formed. Hydrothermal vents in the deep ocean typically form along mid-ocean ridges, such as East Pacific Rise and Mid-Atlantic Ridge (Figs. 3 and 4). In contrast to the classical Miller experiments, which depend on the external sources of energy such as simulated lightning or ultraviolet irradiation, Wächtershäuser argued that life was more likely to have arisen in the exotic conditions near volcanic vents, driven by metal catalysts. Wächtershäuser systems come with a built-in source of energy—sulphides of iron and other minerals (e.g., pyrite) which help in evolving autocatalytic set of self-replicating, metabolically active entities that would predate life forms known today. Geologists have recently discovered 1.43 billion year-old fossils of deep sea microbes, providing more evidence that life may have originated on the bottom of the ocean (Li and Kusky 2007). The ancient black smoker chimneys, unearthed in a Chinese mine, are nearly identical to archaea and bacteria—harboring structures found on seabeds. These chimneys, which can rise up to 60 m in height, develop at submerged openings in the earth's crust that spew out mineral-rich water as hot as 400°C compared to almost freezing tempera-

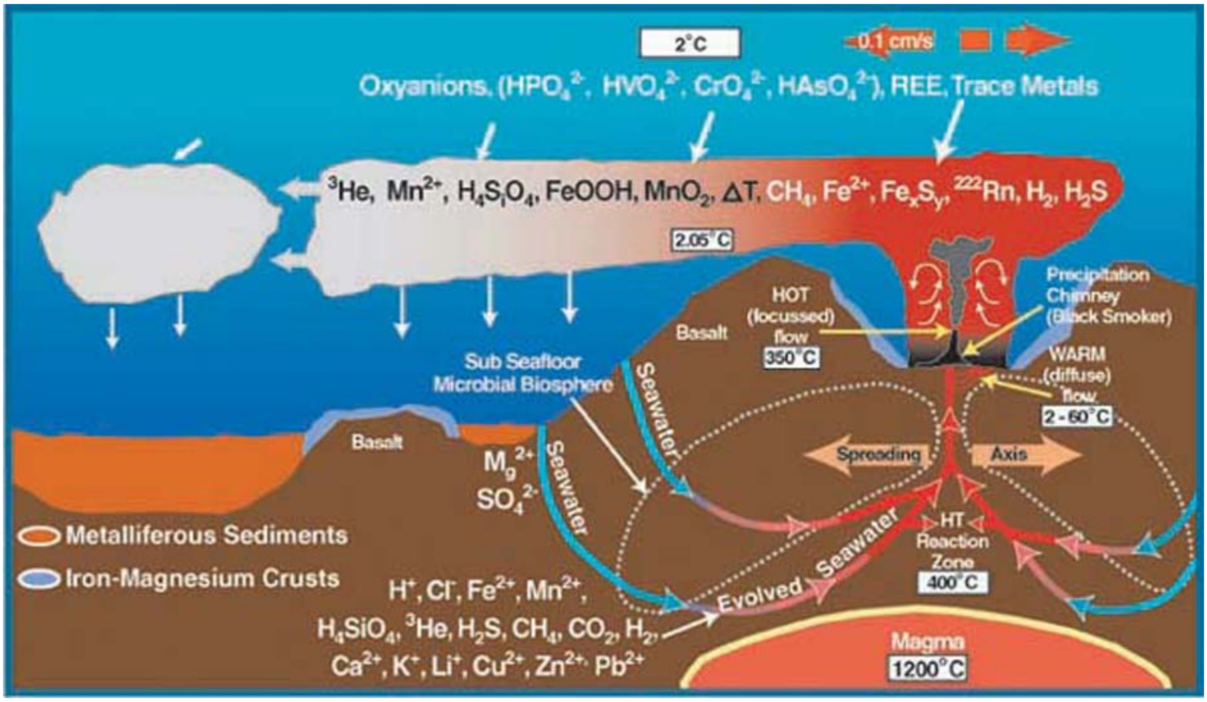

Fig. 4 Deep sea vent biogeochemical cycle diagram. Credit: http://en.wikipedia.org/wiki/Image:Deep_sea_vent_chemistry_diagram.jpg

ture (∼2°C) for the surrounding deep water ocean waters. Arqueobacteria, that do not depend on sunlight or oxygen, move into fragile chimneys that grow around the vents, and feed on the dissolved minerals, particularly H_2S to produce organic material through the process of chemosynthesis. Interestingly, all bacterial molecules are normally destroyed at 150°C. The above instance appears to be reinforcing the views of Wachtershauser and those of Martin and Russel that the first cellular life forms may have evolved and originated on the bottom of the ocean (Martin and Russel 2002).

7 Other extremophiles

Hardy microbes (Brack et al. 1994) have been found to thrive in other extreme environments such as extreme acidic, alkaline, and saline as well. "Acidophiles" thrive in a caustic environment with the pH level at or below 3, and "alkaliphiles" favor a habitat in an alkaline environment with pH levels of 9 or above. Most natural environments on the earth are essentially neutral having pH values between 5 and 9. Highly acidic environments can result naturally from geochemical activities such as the production of sulfurous gases in hydrothermal vents and some hot springs. Acidophiles are also found in the debris leftover from coal mining. Alkaliphiles live in soils laden with carbonate and in so-called soda lakes as those found on Egypt, the Rift Valley of Africa, and the western US. "Halophiles" make their home in intensely saline environments, especially in natural salt lakes like the Great Salt Lake (US). A new species of living bacteria, "Spirocheta Americana" has been found flourishing deep inside California's Mono Lake's salty-alkaline mud where no oxygen could reach (NASA News Release 2003). Semidormant bacteria found in ice cores over a mile beneath the Antarctica lend credibility to the idea that the components of life might survive on the surface of icy comets. "Psychophiles" are the other cold-loving microbes that thrive in the most frigid places like the Arctic and Antarctica that remain frozen almost throughout the year. Recent experiments suggest that if bacteria were somehow sheltered from the radiation of space, perhaps inside a thick meteoroid, they could survive in dormant state for millions of years. Dormant bacterial spores have been reported to have been revived in 30 million year old amber. Then there are bacteria that do not rely on photosynthesis for energy at all. In particular, "endolith" bacteria using chemosynthesis have been found to survive in microscopic spaces within rocks, such as pores between aggregate grains, and in subterranean lakes. "Hypolith" bacteria live inside rocks in cold deserts. Of all different strains of bacteria on earth, those in genus "Deinococcus" are really a hardy bunch. They are extremely resistant to ionizing radiation as well as nuclear radiation. "Deinococcus geothermalis" can handle the harshest environment on the planet—its favored habitat includes nuclear plants. "Deinococcus radiourans" is capable of withstanding 500 times radiation that will easily kill a human—with no loss of vitality.

8 Extremophiles and astrobiology

Astrobiology is the field concerned with forming theories about the distribution, nature, and future of life in the universe. Astrobiologists are particularly interested in studying extremophiles, as many organisms of this type are capable of surviving in environments similar to those known to exist on other planets. For example, Mars may have regions in its deep subsurface permafrost that could harbor "endolith" communities. The subterranean ocean of Jupiter's Europa may harbor life at the hypothesized hydrothermal vents at the ocean floor. Another hyperthermophile that lives in deep sea chimneys—the methane-producing archaean, "methanopyrus" is being studied to help understand how the world's earliest cells survived the harsh environs of the primitive earth. Even acidic clouds of Venus are suspected of harboring life. The mysterious dark patches in the Venusian atmosphere may be related to the vast communities of hardy microbes comparable to the terrestrial extremophiles (Stuart 2002). Moreover, bacteria are space hardy, and have the capability to sustain extremes of temperature and pressure. Biological catalysts are able to convert hydrogen and carbon dioxide or carbon monoxide into methane with ease. The class of bacteria known as "methanogens" is capable of achieving this fact. Given the fact that methane is found in large quantities in the atmospheres of the four Jovian planets—Jupiter, Saturn, Uranus, and Neptune, the presence of "methanogens" cannot be ruled out. Also, Titan, the largest satellite of Saturn, where a methane lake the size of the Caspian Sea has been spotted, and the presence of methanogens there, too, could not be ruled out (Stofan et al. 2007).

9 Panspermia

Panspermia (Warmflash and Weiss 2005; Wickramsinghe 1974; Hoyle and Wickramsinghe 1977; Hoyle et al. 1982) provides an alternative to earthly "abiogenesis" (generation of life from nonliving matter). It hypothesizes that primitive life may have originally formed extraterrestrially. It supports the view that the seeds of life are ubiquitous, and they may have delivered life to the earth as well as to the other habitable bodies in the universe. As early as March 1903, Svante Arrhenius formalized the concept that microbe spores were propelled through space by radiation emitted by stars, and they were possibly the seeds of life on earth (Arrhenius 1903). It is discussed nowadays as a serious alternative to a purely terrestrial origin of life. As per this theory, life arises elsewhere in the universe, but seeds of life can travel across galaxies as "life spores" protected in comets from ultraviolet radiation and seed the planets in the solar system and elsewhere in the universe. Bacterial spores are known to survive ultraviolet exposure in satellite experiments lending support to the hypothesis of panspermia for the origin of life wherein comets made mostly of ice and organic dust could carry bacterial life across galaxies protecting it from ultraviolet radiation during its traverse in the interstellar space, and deliver seeds of life to planets like earth. Panspermia requires life to have been introduced to earth some 4 billion years ago, with an ongoing incidence of microorganisms arriving on the earth from the space, hitchhiking on comets and meteorities, that continues until today. Interesting prediction of the panspermic hypothesis is that life throughout the universe is derived from the same ancestral stock. Fred Hoyle and Chandra Wickramsinghe have been among the prominent proponents of this hypothesis who believed that life forms continue to enter the earth's atmosphere, and they may also be responsible for epidemic outbreaks, new diseases, and the genetic novelty necessary for microevolution (Hoyle and Wickramsinghe 1979). They firmly support the convention that a life-bearing comet—rich in organic content struck the earth about 4 billion years ago, depositing its cargo of primitive cells—the forerunner of all life today. The dominant source of exogenous organics to early earth is believed to be interplanetary dust particles, which appear to be ∼10% organic by mass, and decelerate gently in the atmosphere and so can deliver their organics intact. Particles <1 μm across do not burn up in the atmosphere, but fall gently to the ground. As per one estimate, the earth is sweeping 3,000 tonnes of interplanetary dust every year, providing about 300 tonnes of organic materials to the earth annually (Chyba and Sagan 1992).

The first identification of organic polymers in interstellar grains was made by Wickramsinghe in 1974 and the first association of a biopolymer with interstellar dust discovered in 1977 by Hoyle and Wicramsinghe. The first laboratory spectral signature characteristic of freeze-dried bacteria was identified by Al-Mufti in 1982 during analysis of infrared absorption by dust in the range of 2.9–3.9 μm waveband for the galactic center source GC-IRS7 (Hoyle et al. 1982). Hoyle and Wickramsinghe firmly believed that dust grains in the interstellar medium had a complex organic composition, and their inclusion within comets led to transformation of prebiotic matter into primitive bacterial cells. Inerstellar and cometary dusts have been found to have spectroscopic properties consistent with widespread occurrence of microbial material. The preexisting viable bacterial cells derived from interstellar space are believed to have been included in comets in the primitive solar system 4.5 billion years ago (Hoyle and Wickramsinghe 1977). The cometary collisions with the earth may themselves have injected life onto the earth on several occasions during the Hadean epoch—some 4.3–3.8 billion years ago. Comets, residing in the Oort cloud within the outer reaches of the solar system with profuse of organic materials are believed to be the ideal sites for origin of simple living organisms. The young earth could have also received more complex molecules with enzymatic functions, molecules that were prebiotic but part of a system that was already well on its way to biology. After landing in a suitable habitat on our planet, these molecules could have continued their evolution to living cells. Thus, life could have roots both on earth and in space (Warmflash and Weiss 2005).

Stellar nucleosynthesis of heavy elements such as carbon allowed the formation of organic molecules in space, which appear to be widespread in our galaxy. Discovery of "glycine" (CH_2NH_2COOH), simplest amino acid (building block of protein), in Sagittarius B2, a dense cloud of interstellar gas at the very heart of the Milky Way, bolsters the view that interstellar medium may have played a pivotal role in the prebiotic chemistry of earth (Kuan et al. 2003). Using radio astronomy, researchers claim that the spectral fingerprint of glycine at the frequency range of 90 to 265 GHz is the first step in establishing the critical link between amino acids in space and the emergence of life in the solar system. Until March 2008, an assortment of 140 different chemical compounds including several organic compounds with C, H, O, and N as major constituents had been identified in the interstellar clouds, circumstellar matter, and comets (New organic molecules in space 2008). They range in complexity from the simplest diatomic (H_2) through familiar ones like hydrogen cyanide (HCN), methane (CH_4), methanol (CH_3OH), formic acid (HCOOH), ethanel (CH_3CH_2OH) to thermally hardy polycyclic aromatic hydrocarbons (PAHs). Figure 5 provides near infrared spectrum of ethanol.

In a balloon experiment performed by Narlikar et al. on January 2001, air samples at heights ranging from 20 to 41 km over Hyderabad (India)—above the tropopause where mixing from the lower atmosphere is unexpected, a vast amount of viable but not-culturable microorganisms were discovered along with three species of microorganisms that very much resembled their known terrestrial counterparts namely, cocus (spherical bacterium), bacillus (rods), and a fungus identified as "engyodontium albus" reinforcing the concept of panspermia (Narlikar et al. 2003; Wainwright et al. 2002).

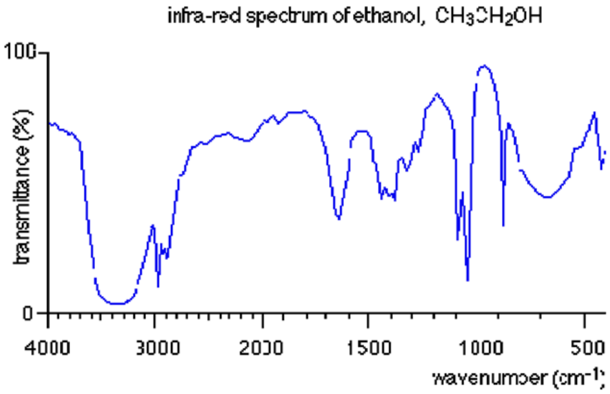

Fig. 5 Near infrared spectrum of ethanol. Credit: http://www.chemguide.co.uk/analysis/ir/interpret.html#top

There are also reports of fossilized microorganisms being found inside a 4.6 billion year-old Murchison meteorite (Kvenvolden et al. 1970) that crashed to the earth (Australia) in 1969. The organisms have been identified as bacteria capable of surviving in the extreme environments that lend credibility to the belief that life could have first evolved elsewhere in the deep space before a meteorite or comet seeded the earth. Over the past 20 years, 30 meteorites have been found on the earth that originally came from the Martian crust, based on the composition of gases trapped within some of the rocks. In a disputed claim, a meteorite known as ALH 84001 originating from Mars was shown in 1996 to contain microscopic strucutures resembling terrestrial microfossils and a variety of organic molecules including PAHs (Mckay et al. 1996). In the meanwhile, biologists have detected organisms durable enough to survive journey from Mars to earth, inside such meteorites. Researchers using the world's largest radio telescope—the Arecibo Observatory in Puerto Rico have detected an amino acid precursor, "methanimine" in the far-flung galaxy Arp 220—some 250 million light years away from earth, which provides fresh evidence that life has the potential to evolve throughout the universe. Methanimine can form the simplest amino acid, glycine, when it reacts with hydrogen cyanide and then water, or formic acid (Salter 2008). Earlier evidence of formaldehyde, ammonia, hydrogen cyanide, and formic acid was found in the star-forming region.

10 Concluding remarks

Given the potential of extremophiles to survive in highly inhospitable environments on the earth, the possibility of life on extraterrestrial bodies like Mars, Europa, Titan, Enceladus, and Triton in the solar system cannot be ruled out. Also, the study of the planetary geology reveals that our solar system could have many worlds with liquid water, the essential ingredient for life. Recent data from NASA's Mars Exploration Rovers also corroborate the speculation that water has at least intermittently flowed on the red planet in the distant past (Warmflash and Weiss 2005). Moreover, studies based on data from NASA's Mars Reconnaissance Orbiter have revealed that the red planet once hosted vast lakes, flowing rivers, and a variety of other wet environments that had potential to support life. It is not unreasonable to hypothesize that life existed on Mars long ago and perhaps continues there even today. Besides, analyzing data gathered by the Cassini spacecraft, scientists have recently confirmed the presence of heavy negative ions about 10,000 times the mass of hydrogen in the upper regions of Titan's atmosphere

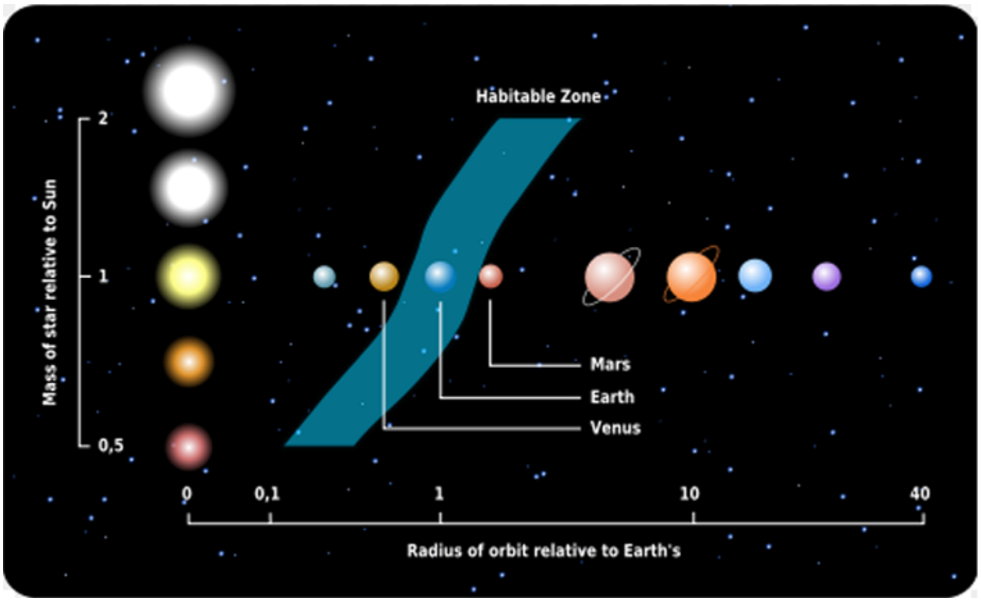

Fig. 6 Planetary habitability chart showing where life might exist on extrasolar planets based on our own solar system and life on Earth. Credit: http://en.wikipedia.org/wiki/Image:Habitable_zone-en.svg

which is devoid of oxygen and is comprised mainly of nitrogen and methane. These particles may act as building blocks for complicated organic molecules—the harbinger for earliest form of life in Titan's atmosphere (Richardson et al. 2007). Cassini's radar mapping also reveals that Titan is just covered in carbon-bearing material. It is a giant factory of organic materials with several hundred lakes and seas of hydrocarbons (methane and ethane). Life may have even got a foothold on torrid Venus as well. The Venusian surface is probably too hot and under too much atmospheric pressure to be habitable, but the planet could conceivably support sulfur-based microbial life high in its atmosphere as do sulfur-eating "chemotrophs" on the earth.

Keeping in view the great survival instinct of extremophiles to thrive in the harshest of environment on the earth, the possibility of traces of life forms being found on billions of unexplored planetary bodies outside our solar system cannot be negated as well. Out of over 300 exoplanets detected beyond our solar system till date, one extrasolar planet (Jupiter-like gaseous planet) named "HD209458B", located at some 150 light years from the earth in the constellation of Pegasus, is believed to be harbouring water vapor in its atmosphere giving rise to the speculation of the presence of life-supporting microbes in its atmosphere based on the analysis of the infrared spectrum in the range of 7.5–13.2 µm (Ma et al. 2007). The planetary habitability chart (Fig. 6) shows where life might exist on extrasolar planets based on our solar system and life on earth. Recent computer simulations of the known extrasolar planetary systems suggest about half of the hitherto discovered exoplanets could harbour earth-like world raising possibility of traces of life-bearing molecules being found thereon.

Despite the strong possibility of the existence of a large number of extraterrestrial life-systems in the universe, there remain nagging uncertainties in regard to the timing of commencement of the process of evolution of life on the primitive earth and elsewhere in the universe. Though panspermia provides a satisfactory explanation to the origin of life on earth and elsewhere in the universe it, however, fails to address the long-standing riddle as to when and where precisely life originated first in the universe, nor does it provide any clue as to how transformation from prebiotic matter into primitive bacteria was brought about in the early epoch of the earth either. Evidence from meteorites/comets and experiments that simulate the conditions on the early earth suggests that probably a combination of terrestrial and extraterrestrial factors were responsible for jump-starting the process of transforming prebiotic organic compounds into entities that we call "life" on earth.

There is growing evidence to support the idea that the emergence of catalytic RNA was a crucial early step in the evolution of life on earth. How that RNA came into being, however, remains unknown so far. Moreover, the "RNA world" hypothesis does not seem to provide a satisfactory explanation to the initiation of mechanism of "self-replication" in organisms in the early history of earth, which is so crucial to the understanding of the process of evolution of life on our planet and other habitable bodies in the universe (Orgel 2006). Experiments involving biologically produced RNA have so far failed to provide concrete proof regarding the RNA world being the pathway between nonlife and life. Moreover, despite development of sophisticated biotechnology tools in the recent years, scientists still have not been successful in transforming inanimate matter into life in the laboratory. Besides, the underlying uniformity of life on the earth, with all modern organisms sharing the same DNA-based mechanism for genetic transmission, is indicative of the fact that life emerged here only once during the planet's entire history (Miller and Orgel 1974; Burlinski 2006). It is ironic that crucial timing hitherto remains unknown to the mankind.

Ever since Oparin and Haldane initiated the modern theory of life's origin from nonlife in 1930s, we have learnt much about how life operates, but almost nothing about how it originates. It is a puzzle whose mystery will perhaps remain unknown to the humanity ad infinitum.

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