ORIGINS OF LIFE: A COMPARISON OF THEORIES AND APPLICATION TO MARS

WANDA L. DAVIS[1,2] and CHRISTOPHER P. McKAY[2]
[1] *SETI Institute*
[2] *Space Science Division, NASA Ames Research Center, Moffett Field, CA 94035-1000*

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Abstract. The field of study that deals with the origins of life does not have a consensus for a theory of life's origin. An analysis of the range of theories offered shows that they share some common features that may be reliable predictors when considering the possible origins of life on another planet. The fundamental datum dealing with the origins of life is that life appeared early in the history of the Earth, probably before 3.5 Ga and possibly before 3.8 Ga. What might be called the standard theory (the Oparin-Haldane theory) posits the production of organic molecules on the early Earth followed by chemical reactions that produced increased organic complexity leading eventually to organic life capable of reproduction, mutation, and selection using organic material as nutrients. A distinct class of other theories (panspermia theories) suggests that life was carried to Earth from elsewhere – these theories receive some support from recent work on planetary impact processes. Other alternatives to the standard model suggest that life arose as an inorganic (clay) form and/or that the initial energy source was not organic material but chemical energy or sunlight. We find that the entire range of current theories suggests that liquid water is the quintessential environmental criterion for both the origin and sustenance of life. It is therefore of interest that during the time that life appeared on Earth we have evidence for liquid water present on the surface of Mars.

Introduction

From the geological record, there is convincing evidence for life on Earth 3.5 Ga in the form of microfossils and stromatolites (lithified layers of microbial material within sediments (Schopf, 1983). Analysis of the morphology of these fossils suggests that they are ancestors of the modern cyanobacteria – and hence oxygenic photoautotrophs (Schopf and Packer, 1987; Schopf, 1993). Further back in time, the carbon isotope ratio of sedimentary carbon may indicate life (again phototrophic) within the 3.8 Gyr old Isua sediments (Schidlowski, 1988). The significance of these early dates becomes clear in the context of the formation of Earth (Froude *et al.*, 1983; Schopf and Packer, 1987; Schidlowski, 1988; Bowring *et al.*, 1989; Schopf, 1993; DePaolo, 1994) (see Figure 1). The end of the late bombardment – during which time the inner solar system is impacted by carbonaceous asteroids and comets – is usually put at 3.8 Ga and the intense rain of objects could well have rendered the Earth uninhabitable before that time (see e.g., Maher and Stevenson, 1988). Thus, it appears that life appeared rapidly – maybe instantaneously in geological timescales – once the proper environment was provided on the early Earth (Oberbeck and Fogleman, 1989, 1990).

In addition to the geological record there is a genetic record of the evolution of life on Earth contained within the vast genome of life. Comparative studies

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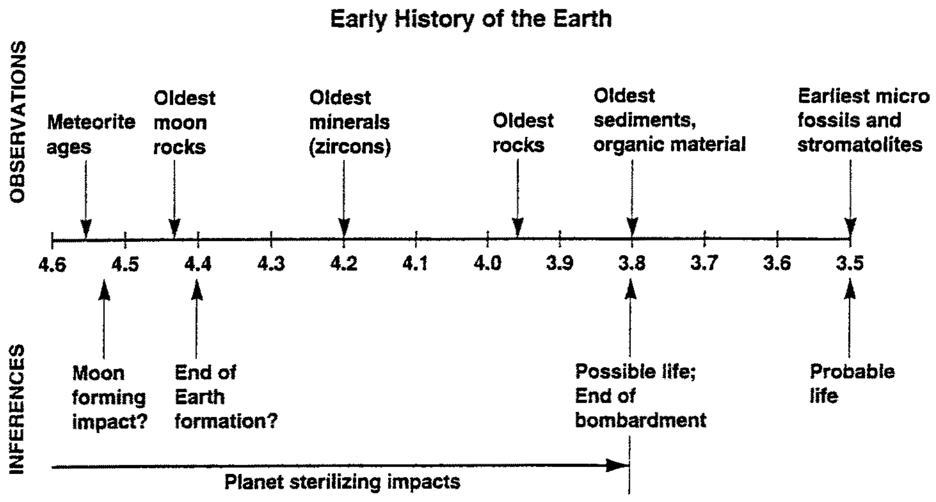

Fig. 1. The early history of the Earth from its formation until the first convincing evidence for life (Froude *et al.*, 1983; Schopf and Packer, 1987; Maher and Stevenson, 1988; Schidlowski, 1988; Bowring *et al.*, 1989).

of the ribosomal RNA have yielded family trees for virtually all life on Earth (Woese, 1987). One interesting feature of these trees is that the organisms most similar to the common ancestor are thermophilic, sulfur-metabolizing organisms. This could be due to one of three possibilities: 1) the origins of life are somehow related to hot sulfur-rich environments (Maher and Stevenson, 1988); 2) there was a biological catastrophe, such as an ocean-boiling impact, from which only organisms in thermophilic sulfur-rich environments survived (Sleep *et al.*, 1989); 3) it is mere chance (Monod, 1971). It is likely that only when we have data about life on another planet will we be able to evaluate these alternatives. Studies of the genome can also provide clues to the origins of life. Eigen *et al.* (1989) argue that the genetic code is not older than but almost as old (3.8 ± 0.6 Gyr) as the Earth – consistent with an origin on Earth.

Theories for the Origins of Life

"...some current bottlenecks in biology, such as the problem of the origin of life ..., are primarily due to a deficiency of certain basic facts." (Mayr, 1982). Indeed, the evidence of the events that led to the origins of life on Earth appears to have been erased from the geological record. This leaves significant range for theories of the origins of life. A taxonomy of the current scientific explanations for the appearance of life on Earth is shown in Figure 2 and reveals two broad categories. Theories that suggest that life originated on Earth (Terrestrial in Figure 2) and theories that suggest that life was carried to Earth from elsewhere (Extraterrestrial in Figure 2). The terrestrial origins of life theories can be further subdivided into those which

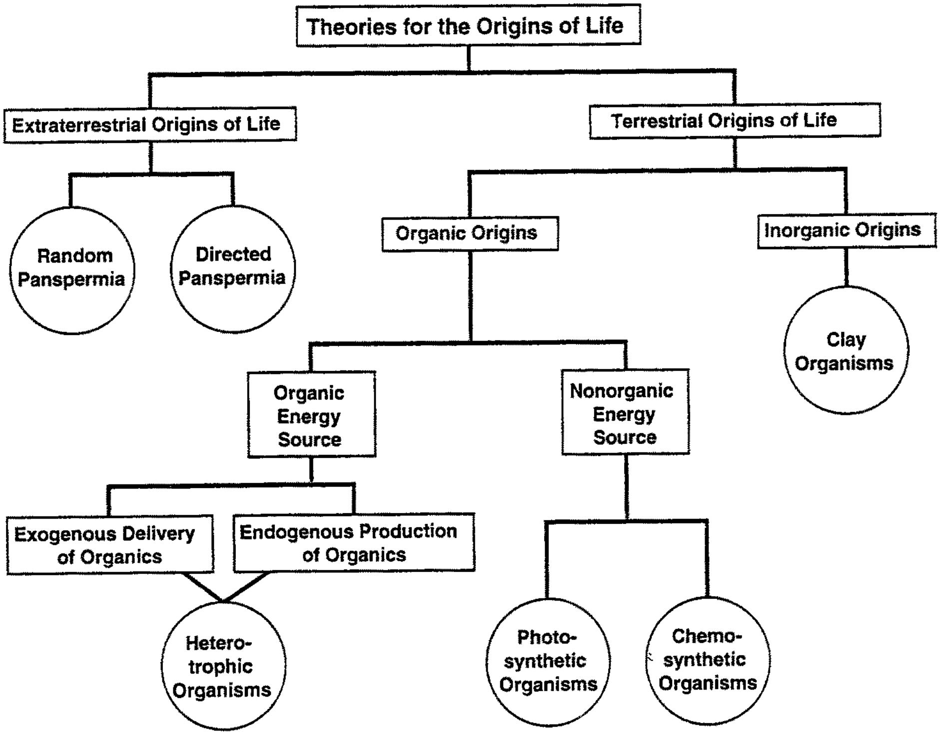

Fig. 2. Diagram of the theories for the origins of life on Earth.

postulate that the structure of the first organism was organic (carbon-based) and those that postulate an inorganic origin (mineral-based). Theories based on an inorganic origin suggest that life's first components were mineral substrate lattices that organized and synthesized clay organisms. These organisms would have been replaced via natural selection by the biochemical organisms we see today. Theories with organic origins suggest that the initial life forms were composed of the same basic building blocks that we find in life forms today, organic material. If life arose in organic form then there must have been a prebiological source of organics from which these first organisms evolved. Some theories suggest that all or part of these organic substances were produced on the Earth itself. Other theories suggest that some exogenous delivery of organics from space – for example by comets or asteroids – was required. The theories for organic origins differ mainly in the type of primal energy source envoked: photosynthetic, chemosynthetic or heterotrophic. The chemotrophs and phototrophs use nonorganic sources of energy, chemical energy and sunlight respectively, whereas heterotrophs acquire their energy by consuming organics.

Extraterrestrial Theories

The concept of panspermia was first suggested by Arrhenius (1908). He speculated that spores from another planetary system propelled by the pressure of sunlight could have seeded the Earth. More recent panspermia theories (labeled Random Panspermia in Figure 2) suggest that life exists in outer space and is transported to planetary surfaces by meteorites, asteroids or comets (Hoyle and Wickramasinghe, 1978; Hoyle and Wickramasinghe, 1979a,b,c; Irvine *et al.*, 1980). It also has been suggested that bacteria are widespread in the interstellar medium and are transferred to Earth's planetary surface (Hoyle and Wickramasinghe, 1979a,b,c). Alternatively, panspermia may have operated within our own solar system, obviating the need to survive long periods in interstellar space. Life may have been ejected from another planet in our solar system by impact and jettisoned to Earth (Melosh, 1988; Moreno, 1988). This requires that for some reason the origin of life was more facile on another planet in our solar system – despite the observation that all the other planets are inhospitable to life at the present time. The SNC meteorites are proof that impacts can send material from Mars to Earth. Related to random panspermia is the suggestion that life may have been purposely spread through space (Directed Panspermia in Figure 2) from another planet through the action of intelligent beings (Crick and Orgel, 1973; Crick, 1981).

Extraterrestrial origins of life pose few constraints on the first appearance of life on Earth – the earliest organism on Earth disembarks fully developed. The primary constraints indicated in panspermia are that the organisms survive the journey through space to Earth and that the surface of the Earth be suitable for their growth. Several workers have looked at the viability of spores and other current forms of life during the Long Duration Exposure Facility experiments in space and in laboratory simulations and cannot rule out the possibility that bacteria and their spores could survive long transits in space (Horneck, 1981; Weber and Greenberg, 1985; for reviews see Davies, 1988; Horneck *et al.*, 1994). For a planet to be receptive to the organism that fell to Earth a suitable environment would have to exist. Clearly this requires available energy, probably as sunlight, suitable chemical compounds and liquid water on the planetary surface.

Terrestrial Theories

The other major branch of Figure 2 are those theories that assume that life originated on Earth sometime before 3.5 Ga. The clay theories for the origins of life on Earth postulate that the earliest organisms were inorganic and evolved from clay crystal compounds (Cairns-Smith, 1965; Hartman, 1975a,b; Ponnamperuma *et al.*, 1982, Cairns-Smith and Hartman, 1986). Through the process of natural selection the clay crystal compounds would have developed increasingly sophisticated biochemistry. Clay crystals would have functioned as the earliest genetic information storing material – the primitive gene – that assembled organic molecules into replicating systems. The clay organisms would have been able to replicate, mutate and evolve. Evolution would have led to the development of ever more sophisticated organic systems eventually obviating the need for clay materials. Even without clay life, clay surfaces could have played a role in forming organic molecules (Bernal, 1951). More recently, laboratory experiments have shown that clay minerals catalyze the formation of RNA oligomers (Ferris and Ertem, 1992; Prabahar *et al.*, 1994), an important step in creating the RNA that was probably the first genetic macromolecule. The only environmental prerequisites for these origins of life theories are the availability of clay minerals and a liquid water environment for the crystallization process to proceed.

The majority of theories for the origins of life on Earth presume organic origins for life. These theories may be categorized into those that require an organic source of energy, the heterotrophs or alternatively those that rely on nonorganic energy sources, the phototrophs and chemotrophs (see Figure 2). The organic material could have been produced on the surface of the Earth by reactions driven by lightning or shock synthesis in a reducing atmosphere. Miller (1953) originally demonstrated the abiotic production of biologically significant organics from electrical discharges into a methane, ammonia, and water mixture – thought at the time to be a simulation of the early reducing atmosphere on Earth. He found that a number of organic compounds were produced including some of the amino acids needed for life. The ease with which organics could be produced under "natural" conditions suggested that they should be widespread in the cosmos. This was confirmed by direct observation of nonbiological organic material, first in carbonaceous meteorites (Kvenvolden *et al.*, 1970) and then in the interstellar medium (Irvine and Knacke, 1989), comets (Kissel and Krueger, 1987), and the surfaces and atmospheres of the planets and moons of the outer solar system – particularly Titan (Encrenaz, 1984; Sagan *et al.*, 1984; Cruikshank, 1987).

Subsequent studies have demonstrated the production of many more biochemical compounds essential to life (for a recent review, see Miller, 1992). On Earth it is assumed that through a series of steps, referred to as chemical evolution, organic matter assembled into the first living cell. Because of the strong experimental and observational support for abiotic production of biochemically relevant organics, this theory for the origins of life on Earth by the self-assembly of organic material produced on Earth is referred to as the "standard theory". The affinity of biochemistry for liquid water suggests that the chemical evolution phase occurred in an aquatic environment. The success of the standard model notwithstanding, it is important to note that no synthetic production of a living cell or organism has ever been achieved and no significant replication of chemical evolution has yet been reproduced in the laboratory (cf. Rebek, 1994a,b; Wintner *et al.*, 1994; for a review see Chyba and McDonald, 1995).

Later studies of the photochemistry of ammonia indicated that, like methane, ammonia would be rapidly decomposed on the early Earth (Ferris and Nicodem, 1972). This led to suggestions that the early atmosphere of Earth would not have been strongly reducing but would have instead been dominated by CO_2, N_2, and H_2O (Owen *et al.*, 1979; Pollack and Yung, 1980; Levine, 1985; Walker, 1985; Hunten, 1993). Laboratory studies using nonreducing atmospheres show that the endogenous production of organics is much more difficult and that yields of these organics are limited, and possibly inadequate, for the subsequent chemical evolution and origins of life (Chang *et al.*, 1983; Stribling and Miller, 1987).

As an alternative to the endogenous production of organics Oró (1961) suggested that organics could be delivered to the Earth by cometary impact. Subsequent studies by other workers (Chyba, 1987; Ip and Fernandez, 1988; Delsemme, 1992; 1995) indicate that Earth could have also acquired much of its ocean of water this way. Prebiotic organics concentrated in cometary water ponds could provide an ideal situation for chemical evolution (Clark, 1988). Chyba *et al.* (1990) showed that a dense CO_2 atmosphere on early Earth would indeed allow intact cometary organics to be delivered in amounts adequate to provide for the origins of life. Other workers have suggested that organic matter could be delivered by meteorites, interstellar dust particles, and in comet dust (Hayatsu and Anders, 1981; Anders, 1989; Zahnle and Grinspoon, 1990). Chyba and Sagan (1992) concluded that the exogenous delivery of organic molecules via these processes could have provided quantities of organics comparable to those suggested to have been produced endogenously in a reduced atmosphere. This volatile delivery in turn would provide a liquid water habitat for the organic molecules to continue chemical evolution leading to the origins of heterotrophic life.

Several workers (Corliss *et al.*, 1981; Shock, 1990; Wächtershäuser, 1990; Pace, 1991; for a review see Holm, 1992) have suggested hydrothermal or geothermal environments as promising sites for the subsurface origins of chemotrophic life. These organisms utilize chemical energy (e.g., $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O + \Delta E$) and are represented today by, for example, various sulfur metabolizing organisms and methanogens. These theories require a geothermal source of reduced gases such as H_2S and a source of chemical energy (redox potential) for biogenesis.

An alternate energy source for the earliest life was suggested by Woese (1979). He suggested that photosynthetic life forms on Earth occurred in a dense CO_2/water atmosphere. Dust particles from Earth carried high into the atmosphere caused the condensation of water droplets. Prebiotic chemistry and the evolution of life took place within these evaporating water droplets in the atmosphere. The primary energy source for prebiotic synthesis would have been solar radiation. These organisms developed the ability to photosynthesize making their own energy from materials in their environment. The critical constraints for these theories for the origins of life are solar radiation, a dense atmosphere, dust and a source of water.

Implications for Mars

The primary evidence that Mars had a more hospitable environment for life in the past is in the form of images taken from orbit showing large dendritic and sinuous valleys (Figure 3) carved on the martian surface (Pieri, 1980; Carr, 1981; Baker, 1982; Tanaka *et al.*, 1992). These features, which imply that liquid water was stable and flowed on the surface of Mars, are enigmatic since under the current atmospheric pressure ($\sim$7 mb) open bodies of liquid water are not stable (Kahn, 1985). The hypothesis that liquid water was thermodynamically stable on early Mars has led to the suggestion that Mars once had a thick, presumably CO_2, atmosphere early in its history (Pollack *et al.*, 1987) possibly with other greenhouse gases as well (Kasting, 1991). The duration of liquid water on early Mars is uncertain but climate model calculations (McKay and Davis, 1991; Schaefer, 1993; Haberle *et al.*, 1994), suggest that the surface pressure of CO_2 atmosphere would have dropped steadily – over timescales no longer than a few hundred million years. The existence of large volcanos is further evidence that Mars once had a more active surface.

Stellar evolution models suggest that the luminosity of the sun 4 Ga would have been about 30% less than it is today (Bahcall and Shaviv, 1968; Boothroyd *et al.*, 1991; Graedel *et al.*, 1991). To maintain surface temperatures warm enough to allow liquid water would have required a much thicker atmosphere (Moroz and Mukhin, 1977; Pollack *et al.*, 1987). CO_2 by itself appears inadequate because it would have been supersaturated (Kasting, 1991). These calculations are globally averaged and more detailed models may resolve this dilemma. Alternatively, additional greenhouse gases may have been required to keep surface temperatures above freezing. It is possible that liquid water may have been present on Mars in regions of sufficient geothermal activity to compensate for the cold conditions. A further possibility is that surface temperatures were quite cold but that liquid water persisted under an ice cover, as is the case in the dry valleys of Antarctica where life persists in perennially ice-covered lakes while the mean annual temperature is − 20°C (Parker *et al.*, 1982; McKay *et al.*, 1985). McKay and Davis (1991) have suggested that similar lakes could exist on Mars at global mean temperatures as low as −40 °C.

Although there remain uncertainties as to how warm the early environment on Mars was and what type of atmosphere sustained that warmth against the faint young sun, it is important to keep in mind that the evidence for liquid water is direct and, on Earth, liquid water is the quintessential requirement for life. In addition to providing an environment suitable for life, liquid water may be necessary in the broader planetary context. The presence of substantial liquid water may be necessary for plate tectonics and deepsea hydrothermal vents. These processes may be an essential part of a habitable world (Chang, 1988).

To approach the question of the origins of life on Mars we will first assume that the origins of life are fundamental and reproducible processes that will occur given

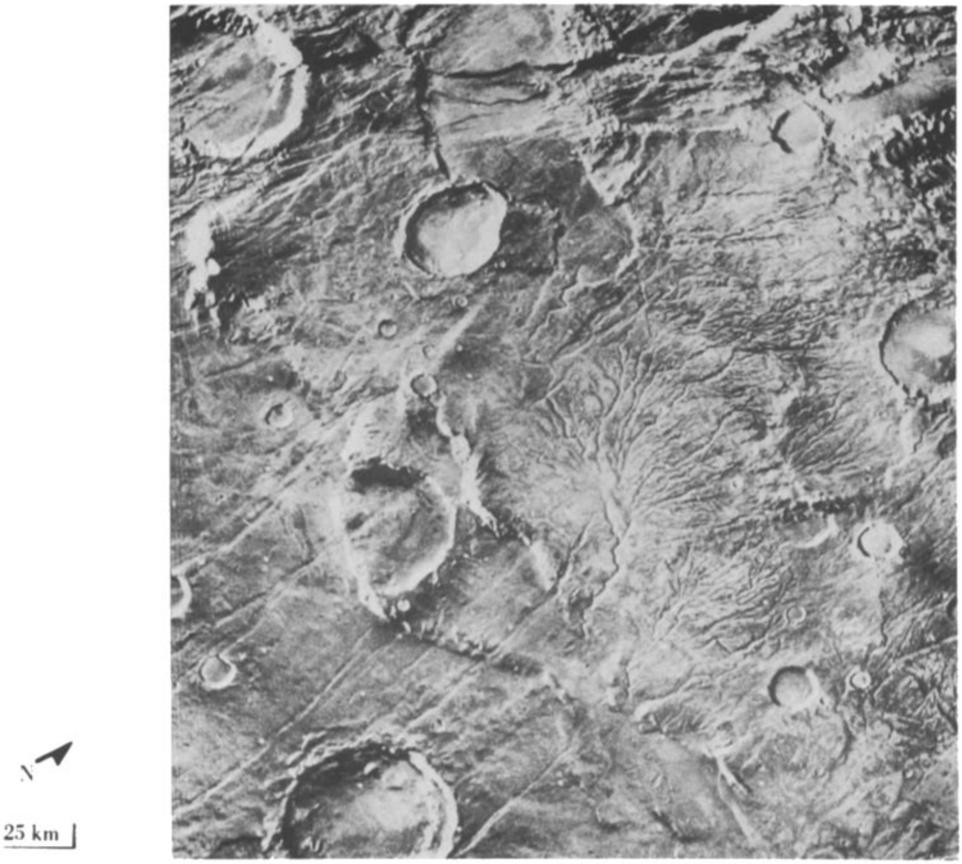

Fig. 3. Dendritic valley system in the ancient cratered terrain (48° S, 98° W; Viking frame 63A09, 250 km across). Valleys such as these are found in the ancient terrain and are most probably formed by surface water flow. The source of the water may have been precipitation or subsurface melting. This evidence for the existence of liquid water habitats on the martian surface 3.8 Ga is the primary motivation for considering the possible origins of life on Mars.

suitable chemical and physical conditions. We are then in a position to compare the necessary conditions for the origins of life as indicated in the suggested theories to the range of environments present on early Mars (McKay and Stoker, 1989). The universal requirement common to all the theories is liquid water. The direct evidence of liquid water on early Mars (Figure 3) is consistent therefore with all theories for the origins of life.

The remaining question is how long this water must persist for life to form. From the geological record (Figure 1) we know that an upper limit for the origins of life on Earth is about 500 million years. Davis and McKay (1994) used a simple climate model to determine the duration of liquid water habitats on early Mars. They find that liquid water habitats could have been maintained under relatively thin ice covers for up to 500 ± 300 million years after the mean annual temperature fell below freezing. Thus the timescale for liquid water on early Mars seems to be comparable to the upper limit on the timescale for life to appear on Earth. An important assumption of this model is that Mars lacked an active geochemical cycle for the recycling of carbon dioxide into its atmosphere. On Earth the recycling occurs as a result of subduction associated with plate tectonics (Berner and Lasaga, 1989). There is no evidence of plate tectonics on Mars – it appears to be a "one-plate" planet (Mutch and Saunders, 1976; Solomon, 1978; Carr, 1981; Davies and Arvidson, 1981; Head and Solomon, 1981). Although, in this regard Sleep (1994) has suggested the possibility of plate tectonics early in martian history. Thus Mars lacks Earth's continuous mechanism – subduction of carbonates and outgassing of CO_2 – for maintaining its atmosphere. In addition Davis and McKay (1994) assume an early history of water on Mars, which declines steadily and eventually disappears. However there is evidence for episodic water on Mars throughout its history (Carr, 1995 and references therein) indicating a more complex climate history.

Besides the general requirement for liquid water the various theories diagrammed in Figure 1 invoke different specific requirements for life. For these theories to be viable explanations for the origins of life on Earth these requirements must have been met in the period before life arose. Aside from celestial parameters such as gravity, radius, spin rate, magnetic field (Luhmann *et al.*, 1992; Dones and Tremaine, 1994) and possibly plate tectonics (Carr, 1981; Sleep, 1994), the early Earth and early Mars are likely to have had the same range of environments. Both early Earth and early Mars had active volcanism and associated sulfurous hydrothermal regions, small ephemeral ponds, large stable bodies of water, meteorite and cometary impacts, anoxic conditions, etc. All the major habitats and microenvironments that would have existed on the early Earth would be expected on early Mars as well. The one exception may have been tidal pools although the solar tide on Mars would still be about 10% of the lunar tide on the contemporary Earth.

The extraterrestrial theories pose the least constraints for the origins of life on Mars. Liquid water is the only essential requirement. The inorganic origins of life require the availability of clay minerals, which are thought to exist on Mars based on the Viking results (Banin *et al.*, 1992). If the earliest organism was organic then an abiotic source of organic material is required. Comets, asteroids, and interplanetary dust would be expected to have delivered organics to Mars with less impact related destruction compared to the Earth owing to Mars' lower escape velocity. The situation is a bit more uncertain if the organics required for life on Earth were produced in a reducing early atmosphere. Mars could have had a similar reducing period but our understanding of the composition and time evolution of the early atmosphere on Mars is incomplete at present (Hunten, 1993). Most models suggest that Mars would have had an early CO_2 atmosphere which would be mildly reducing, and thus abiotic yields of organics may have been inadequate for continued chemical evolution. Sunlight, the prime energy source for autotrophs on Earth, is sufficient on Mars even though Mars is at a greater distant. The hydrothermal energy sources needed for chemoautotrophy on Earth would likely have been available on Mars (Boston *et al.*, 1992). Thus there are no conceptual obstacles to postulating that whatever led to the origins of life on Earth also led to the origins of life on Mars – provided that life sustaining conditions persisted on Mars for an adequate duration.

Other Worlds

The molecule H_2O is common on other worlds in the solar system and there is even a possibility that it exists, or existed, in the liquid state on places other than Earth and early Mars. There may be a liquid water layer beneath a relatively thin ice crust on Europa (Reynolds *et al.*, 1983; 1987). Large comets may have had an initial period with liquid water cores due to heating by ^{26}Al decay (Irvine *et al.*, 1980). Some meteorites show direct evidence of aqueous alteration presumably the result of liquid water present on or in the parent body (Zolensky and McSween, 1988). Recent evidence suggest that this may also be the case for comets (Fomenkova *et al.*, 1992). Finally there is speculation about life in liquid-water clouds on Jupiter (Sagan and Salpeter, 1976) and Venus. The logic applied here to Mars to assess the possible origins of life does not apply to these other planetary environments because while they may have contained liquid water it cannot be argued that they contain the range of habitats that were found on the early Earth. For example, Europa may be a viable candidate for the origins of life based on chemosynthesis in deep ocean vents, but not for the origins of life based on photosynthesis.

A Search for Fossils on Mars

The only definitive test for the origins of life on Mars will be the discovery of fossil evidence of past life on that planet. Sites of past water activity, particularly lakes, are prime targets for a search for fossils on Mars (McKay, 1986; Goldspiel and Squyres, 1991; Farmer *et al.*, 1995). Although the present Mars surface is considered to be both reactive and embedded with oxidants, Bullock *et al.* (1994) have shown that the depth of diffusion for H_2O_2 is less than 3 meters. Kanavarioti and Mancinelli (1990) have suggested that the stability of amino acids indicates that organic matter, as well as organic remnants of meteoritic and cometary bombardment, could have been preserved on Mars beneath the present oxidizing layer for 3.5 Gyr. Bada and McDonald (1995) suggest further that both amino acid homochirality and nucleic acid genetic information could be stable over geologic time in the present polar regions of Mars. If evidence for past life on Mars is found, further effort may be able to trace the evolutionary history of that life and inform us about the nature and environment of the first martian organism. This is more likely to be accomplished on Mars because over half of the martian surface dates back to the late heavy bombardment, 3.8 Ga. Preserved without significant geological or hydrological activity, and under cold anoxic conditions, this surface may hold an intact organic and mineral record of early life on Mars. Thus, even though there may be no life on Mars today, the recorded history of the origins of life process in Earth-like conditions may be more complete on Mars than on Earth. Perhaps studies of Mars will reduce our uncertainty about the phenomenon we call life.

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