CONCEPTS OF LIFE IN THE CONTEXTS OF MARS.

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Introduction: The search for habitable environments and life requires a working concept of life's fundamental attributes. This concept helps to identify the "services" that an environment must provide to sustain life. We must consider the possibility that extraterrestrial life might differ fundamentally from our own, but it is still worthwhile to begin by hypothesizing attributes of life that might be universal versus ones that reflect local solutions to survival on Earth.

Basic attributes and needs of life: Recent studies [1] have identified the following potentially universal attributes: 1) Life must exploit thermodynamic disequilibrium in the environment in order to perpetuate its own disequilibrium state; 2) Life most probably consists of interacting sets of covalently bonded molecules that include a diversity of heteroatoms (e.g., N, O, P, S, etc. as in Earth-based life) that promote chemical reactivity; 3) Life requires a liquid solvent that supports these molecular interactions; 4) Life employs a molecular system capable of Darwinian evolution. These attributes imply key basic universal functions (Fig. 1): 1) Life harvests energy from its environment and converts it to forms of chemical energy that directly sustain its other functions; 2) Life employs "metabolism," a set of chemical reactions that synthesize the chemical compounds required for maintenance, growth and self-replication; 3) Life sustains an "automaton," a multi-component system that is essential for self-replication and self-perpetuation [2].

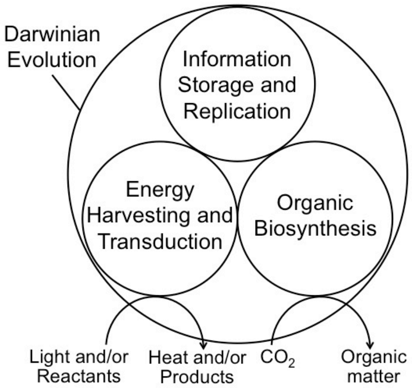

Fig. 1. Life's basic functions

Thus life can be envisioned as a self-sustaining system that is capable of Darwinian evolution and that utilizes free energy to sustain and propagate an automaton (a self-replicator), a metabolic reaction network and functionally related larger structures. These functions specify a level of molecular complexity that, in turn, defines requirements for chemical ingredients, energy and environmental conditions that are essential to sustain life.

Carbon. A key requirement of life is that compounds involved in self-replication and catalytic enzymes must be at least moderately complex. The unique ability of carbon to form highly stable chains, rings, heteroatomic molecules, etc. and thereby create stable complex molecules is thus a crucially important attribute. In contrast, silicon-based molecules having the size and complexity required for biological functions would be highly unstable in the presence of water or other polar solvent. Silicon has a strong affinity for oxygen, which favors the formation of SiO_2 and a wide variety of relatively insoluble solids. In contrast, CO_2 is a gas, it is quite soluble in water, and so it is readily available to supply, participate in and be excreted by biological processes. Carbon is the fourth most abundant element and complex carbon chemistry is pervasive in the universe. So while we cannot assert that ALL life is based on carbon, the chemical versatility and pervasive presence of organic compounds argue that carbon plays a leading role in extraterrestrial life.

Water. A solvent plays critical roles in promoting biological organization [3]. Non-covalent interactions between molecules strongly modulate the structures and functions of living cells [4]. For example, protein folding, interactions between enzymes and ligands, the regulation of gene expression, the self-assembly of boundary structures, and ion transport across membranes are all governed by non-covalent interactions. Non-covalent attractions between molecules must be sufficiently strong that inherent thermal noise cannot dismantle functional configurations. The system should also exhibit stability sufficient for it to function properly over the range of environmental temperatures. But if these interactions are too strong, then a potentially prohibitive expenditure of energy might be required to achieve the regulation of local thermodynamic equilibria that are essential to maintain a functional metabolism. Critical biomolecular interactions would become essentially irreversible. Accordingly the electrostatic interactions between biomolecules cannot be too strong. This requires that the solvent should have a high dielectric constant. Also, interactions between non-polar molecules or groups should be sufficiently strong to favor their organization.Water meets all of these requirements and therefore is an excellent solvent for life. Alternatives such as formamide and di-alcohols also have high dielectric constants and other favorable attributes. However it seems inconceivable that any alternative solvent could approach the cosmic abundance and broad distribution of water. Alternative solvents might support exotic examples of life in some cosmic niches, but water is probably the solvent of choice for the vast majority of extraterrestrial life.

Environmental conditions on Mars: Physicochemical environmental factors (e.g., temperature, pH, salinity, radiation) determine the stability of biomolecules and the availability of energy, nutrients and a solvent required for a living system to maintain biological molecules and structures in a functional state.

Present-day Mars. Organisms can persist in seasonally or episodically dry environments by developing strategies to survive periods of prolonged dryness. However all organisms require a minimum level of water activity [5] at least intermittently so they can become active metabolically and repair damage caused by radiation, chemical degradation or physical disruption that might have occurred during their dormancy. Wherever the martian surface and shallow subsurface are at or close to being equilibrated thermodynamically with the atmosphere, any combination of temperature and water activity is considerably below the threshold conditions required for terrestrial life to propagate. Perhaps highly saline brines can remain fluid at temperatures that can be achieved seasonally at the martian surface, but microbial life as we know it cannot be metabolically active in such brines.

High energy radiation currently at the martian surface is problematic for the evolution and persistence of life. It is doubtful that constructive processes of metabolism could operate more effectively than destructive radiation.

Thus any modern habitable environments are probably restricted to the deep subsurface where liquid water is stable and cosmic radiation is greatly attenuated. Any microbes could obtain energy from redox chemical reactions involving rocks and water [7].

Early Mars. Water-related features and evidence of more vigorous geologic activity indicate that early climates were wetter and perhaps also somewhat warmer. A denser atmosphere would have provided substantial protection from radiation. Redox energy from volcanism, hydrothermal activity and weathering of crustal materials would have been more readily available. The likelihood of any life at the surface would have been greatest during early wetter epochs. Life also might have persisted in long-lived hydrothermal systems, particularly those that had been associated with intrusive magmatism or volcanos [8].

An early intrinsic magnetic field created localized crustal magnetism that generated “mini-magnetospheres” [6] that perhaps provided substantial local protection.

The NASA Mars Exploration Program Analysis Group [9] identified the following key objectives to characterize the past habitability of a site: “(1) Establish overall geological context; (2) Constrain prior water availability with respect to duration, extent, and chemical activity; (3) Constrain prior energy availability with respect to type (e.g., light, specific redox couples), chemical potential (e.g., Gibbs energy yield), and flux; (4) Constrain prior physicochemical environment, emphasizing temperature, pH, water activity, and chemical composition; (5) Constrain the abundance and characterize potential sources of biologically essential elements. For ancient surface environments, these observations basically attempt to reconstruct the ancient climate and its associated processes.”

A search for evidence of habitable environments and life must also consider the potential of a geologic deposit to preserve such evidence. The presentation by Dr. Grotzinger will address this aspect.

Finally, evidence of ancient life should be sought in those environments that have been determined to exhibit a high combined potential for prior habitability and preservation of biosignatures. A biosignature is a substance, structure of pattern that requires a biological origin. Potential biosignatures could be indicated by the following efforts [9]: “(1) Characterize organic chemistry, including (where possible) stable isotopic composition and stereochemical information. Characterize co-occurring concentrations of possible bioessential elements, (2) Seek evidence of possibly biogenic physical structures, from microscopic (micron-scale) to macroscopic (meter-scale), combining morphological, mineralogical, and chemical information where possible, (3) Seek evidence of the past conduct of metabolism, including: stable isotopic composition of prospective metabolites; mineral or other indicators of prior chemical gradients; localized concentrations or depletions of potential metabolites (especially biominerals); and evidence of catalysis in chemically sluggish systems.”

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