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Habitability from a Microbial Point of View

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1. Introduction

Microbial life could have been (or still be) present on a number of the worlds in the Solar System, in the past, today, and possibly in the future, as well as innumerable exoworlds. While the conditions for the emergence of life could have been relatively widespread during the early stages of the evolution of the Solar System, as well as on many other planets and satellites in the Universe, in the Solar System at least, the possibility for evolution from the anaerobic, chemotrophic microbial stage seems to have been limited to the Earth alone. What does this mean for the search for life elsewhere? Will we find it in the Solar System, will we detect it on exoplanets?

2. The origin of life and habitability

It all begins with our understanding of the origin of life. And by life, we consider entities composed of carbon molecules and water, formed of the most common elements in the Universe. On Earth, a variety of environments, from submarine hydrothermal vents, hydrothermal marine sediments and pumice rafts, through volcanic-hosted splash pools to continental springs and rivers, have been proposed for the emergence of life, each with respective advantages and certain disadvantages [see reviews in 1,2]. In the Solar System, it is likely that similar environments existed on the local scale on Mars, especially early in its history and probably Venus. Some of the satellites may have had liquid water containing organic molecules and in contact with hot rocky crusts hosting hydrothermal activity in their early stages, such as Enceladus, Titan, Europa, Callisto and possibly others.

The origin of life requires carbon molecules and essential elements such as H, N, O, P and S, liquid water, and energy sources, all of which were available on the above-mentioned planets and satellites. The important prebiotic processes that led to the origin of cellular life [2] included: (1) concentration of the molecular components participating in prebiotic reactions and control of water activity, (2) stabilisation and structural conformation of molecules, and (3) chemical evolution through complexification. These processes were controlled by the physicochemical conditions of the environment, including element availability, water temperature, pH, ionic strength, energy, irradiation, gradients and molecular diffusion. It is the balance of these parameters over time scales conducive to the emergence of life that dictates which of the proposed types of environments was likely to have been relevant or not (although we do not know how long it took for life to emerge on Earth but the process from prebiotic chemistry to protocell must have been rapid, like a snowball effect, in order to prevent reactions from going backward; this translates into tens – hundreds kyears to a few My – but nobody knows).

C, H, N, O and P are elements with minor endogenic and major exogenic origins on Earth, and probably similarly on Mars [1,3]. While the early Earth was a more or less ocean planet with relatively few, mostly short-lived exposed land masses (could the young Venus have been similar?), the opposite was the case for Mars, while the icy satellites remained totally ocean worlds. On Earth, the subaerial environments, especially, suffer from lack of longevity and exposure to combined high doses of radiation, desiccation etc. While radiation and

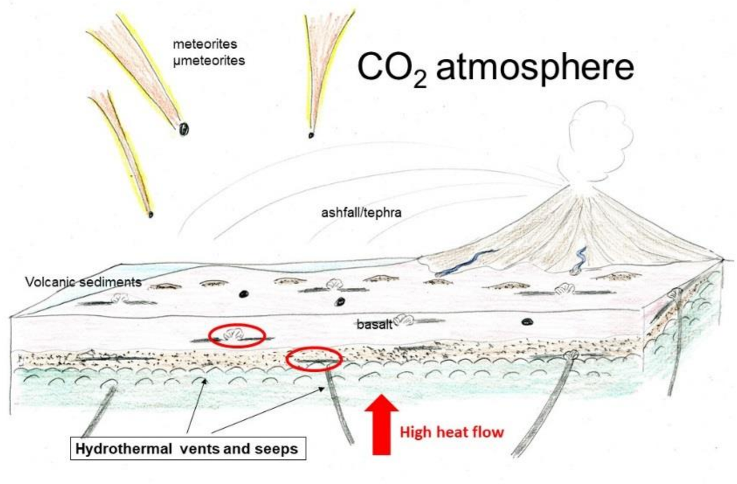

***Figure 1**. Hydrothermal environments in which life could have emerged and which would have favoured biomass development of chemotrophic organisms.*

desiccation have been advocated as potentially useful in terms of an energy source and means of condensation [e.g. 4], respectively, together they are a hazard to the survival of organic molecules. As we understand the origin of life today, these parameters seem to rule out life appearing in streams, rivers or geysers at the exposed surface of any of the planets (Earth, Mars, or Venus), but not such environments as potential habitats for already existing life forms.

This leaves, as possible environments where life could have emerged on Earth, the submarine locations, hydrothermal vents or hydrothermally-charged volcanic sediments, possibly with additions of useful prebiotic molecules formed in other kinds of environments [2] (Fig. 1). On Mars, for instance, early seas and crater lakes on a geothermally hotter planet, subject to volcanism and impacts, could have seen the emergence of life, at different places at different times, despite the lack of total ocean cover [2]. Life forms on all the early planets were likely to have been chemotrophs, possibly initially litho-autotrophs (obtaining their nutrients and energy from inorganic sources) given the importance of mineral surfaces in the origin of life [e.g. 5], accompanied or closely followed by organotrophs (nutrients and energy from organic sources). However, further evolution of life on Earth was spurred by continuous habitability on the scale of hundreds of millions of years, as well as access to sunlight. In the case of Mars, the lack of continuous habitability is likely to have been a hindrance to further evolution towards martian life forms producing more biomass and more easily detectable biosignatures, such as phototrophs that use sunlight as an energy source. Could phototrophs have developed on Venus? We will probably never know. Could it have developed on the icy satellites of the Solar System? They are all far from the Sun, whose luminescence was low at the early stages when liquid water could have been in contact with hot crust on the satellites. Moreover, if any incipient microbes existed, they would be concentrated close to the lithic sources of heat, nutrients and energy, not free-floating in the upper realms of the water column where limited sunlight could reach.

3. Implications for the search for life on extreme habitable worlds?

From our understanding of the early terrestrial environment, when the Earth was anaerobic, hot and colonised by chemotrophs (as well as phototrophs), it is clear that the chemotrophs were most at home and "comfortable" in and around hydrothermal vents, *i.e.* small and localised phenomena [6]. They occurred also on volcanic surfaces at distance from hydrothermal effluents but their biomass development in these cases was limited - and biomass development is important in the search for and detection of traces of life on the planet. The anaerobic phototrophs had the advantage of not being dependent on the nutrient-rich hydrothermal sources, they could invade what we consider to be oligotrophic environments, *i.e.* environments poor in nutrients, because they got their energy from the sun and whatever nutrients there were in the seawater [7]. However, they had to live at shallow water depths, or even on land in the vadose zone [8] or hot springs [9].

Microbes are the archetypal opportunists. This means that, from the microbial point of view, many places on Mars, for instance, could potentially have been inhabited since microbes can colonise even briefly habitable environments. Whether occurring in subtle expression or in "well-stocked" biofilms, traces of chemotrophic microbial life can be preserved in the form of physical fossils or entrapped organic molecules encased a mineral matrix. The biological organic material can also be detrital, *i.e.* transported from its site of formation and deposited elsewhere – over short distances and presuming the minimum of environmental degradation. The important point is rapid encapsulation followed by cementation and preservation of the rock host. Hydrothermal environments, especially, favour microbe and organic preservation, as do other fine-grained materials, such as clays.

Detection of traces of microbial life in the Solar System may be possible on Mars, especially if we can land in the sweet spot where there has been hydrothermal activity to stimulate chemotrophic growth [10]. Detection of traces of life on the icy crusts of the satellites is more challenging. Even if there is life on them and cells are extruded in the plumes from the underlying oceans, the extremely hostile radiation environments bathing the icy crusts make detection of organic molecules challenging. So, Mars is still the best choice in the Solar System. And exoplanets inhabited by phototrophs, of course.

References

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Short Summary

Life could have been/still be present on a number of Solar System worlds, and on innumerable exoworlds, all of them extreme, in the form of mostly simple microorganisms. But Mars is the only planet where we have a likely chance of finding traces of life.