From Sterilized Past, Biological Flourish Today, to Foreseeable Future

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Planets like our planet Earth are formed during star formation, which is of general interest to scientists, because it provides insight into the formation of planetary systems and the synthesis of organic compounds, which could lead to the appearance of life. For Sun-like planetary system, the habitable zone, where liquid water is present on the planetary surface, and the formation of rocky planets are always located at an orbital distance of <10 AU (1 AU = the distance between Earth and Sun = 150 million kilometer). The conditions of chemical and physical environments during the formation of planets, before the disappearance of gaseous disks, are the most crucial to these questions, especially in the regions of disks with radius <10 AU. But, the lifetime of gaseous solar nebulae is less than 10 Myr; this strongly limits the possibility of probing (or finding) them. A step backward is to map the profiles of density, temperature, and chemical composition as a function of radius in protoplanetary disks. However, this requires high spatial resolution; current technology to the chemical and physical conditions for protoplanetary disks in the regions with radius <10 AU is then very limited. Another approach is to observe the chemical and physical properties of planets. The formation mechanism for the discovered extrasolar planets provides important and unique clues to the conditions of chemical and physical environments in the inner regions (<10 AU) of solar nebulae.

Many organic molecules have been identified in comets, meteorites, and the interstellar medium. The most complex of these are likely formed and synthesized on grain surfaces, avoiding direct exposure to the interstellar UV field. The findings of organic compounds in space greatly broaden our perspective and revive an old proposal that the first life on Earth may have been delivered from space. The recent discovery of extremophiles (“superbugs,” which can survive in extreme conditions, e.g., extreme heat, extreme cold, extreme pressure, darkness, and toxic-waste waters) expands our view of life and suggests that simple life, if not so complex as animals and human beings, is ubiquitous. From the discoveries of organic compounds in space and bacteria in extreme conditions on the Earth, we learned that (1) Dust grain surface chemistry is the key to synthesizing complex molecules, and (2) Life as we know it requires liquid water.

Figure 1 shows a diagram of a postulated transition from chemical to biochemical evolution. Titan, a satellite of Saturn, is the only object other than Earth in the solar system that possesses a thick nitrogen atmosphere (1.5 bar). Methane constitutes ~2.5%. The coupled photochemistry between methane and nitrogen leads to enrich production of hydrocarbons and nitriles, which could have been available in the very early Earth for providing micro-organisms, if present, "food." A step further is the condition similar to Europa, a satellite of Jupiter, which is located at the point where a bottleneck that transitions from the chemical to biochemical regime occurs. A prevailing view, expressed by Lunine (1999), is that "*Europa, with a possible liquid ocean, might support life, but agreeable conditions may be so short-lived that this body always stands just on the threshold of life's origin.*" An internal source of heat is required to maintain the liquid ocean, the likely sources being radiogenic and primordial heating (left over from the formation of Europa). The interior of Europa is likely to be rocky. The biogenic elements, e.g., carbon, nitrogen, sulfur, and rare metals, should be abundant if life is to persist, though cometary delivery is also another potential source.

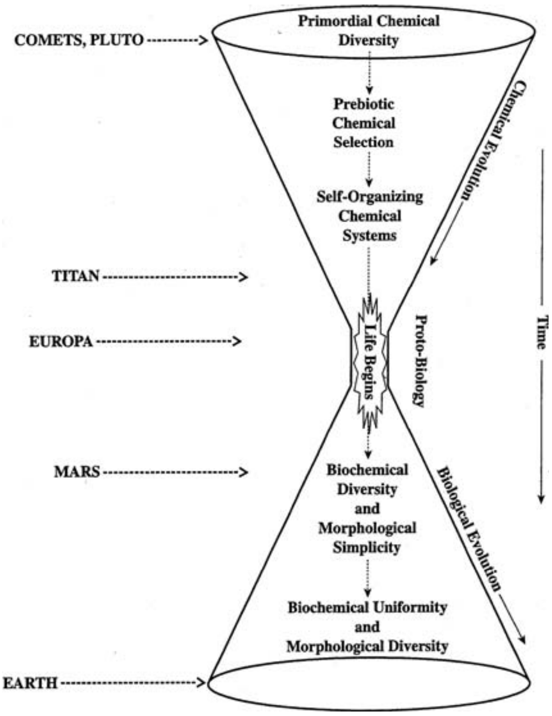

Figure 1. A schematic diagram illustrating the evolution from chemical to biochemical regime. After Lunine (1999).

Recently at the end of 2005, the Cassini spacecraft (an NASA mission to Saturn) discovered unusual activity that water vapor plumes ejected from the south pole of the Saturnian satellite, Enceladus. With its significant geothermal energy source propelling these plumes >80 km from the surface of the moon and the ensuing large temperature gradient with the surrounding environment, it is possible to have the weathering of rocks by liquid water at the rock/liquid interface. For the cases of the putatively detected salt-water oceans beneath the ice crusts of Europa, an isolated subsurface ocean without photosynthesis or contact with an oxidizing atmosphere will approach chemical equilibrium and annihilate any ecosystems dependent on redox gradients unless there is a substantial alternative (for example, geothermal) energy source. This thermodynamic tendency imposes severe constraints on any biota that is based on chemical energy. On Enceladus, the weathering of rocks by liquid water and any concomitant radioactive emissions are possible incipient conditions for life. The combination of a hydrological cycle, chemical redox gradient and geochemical cycle give favorable conditions for life.

A step further shown in Figure 1 is Earth-like environment and its evolutionary history. One of the major mysteries in the history of life is the origin of the enzyme systems that protect cells from the oxidative damage of molecular oxygen. The significance is that without oxygenic photosynthesis complex life like our human beings would never appear at the surface of the planet. Protection from such oxidative damage is necessary before oxygenic photosynthesis could evolve, but oxygenic photosynthesis is virtually the only source of this oxidant. The chicken-and-egg nature of this problem was recognized back in 1977 by Bill Schopf at UCLA, who noted that, without oxygen mediating enzymes, the first photosynthetic cell to release O_2 would kill itself. One possible solution is hydrogen peroxide, since it is capable of being both a powerful oxidant and a reductant and since the oxidation of H_2O_2 to O_2 is fully within the oxidative capabilities of reaction centers from existing anoxygenic photosynthetic bacteria. However, in order for photosynthetic bacteria to be in power, processes that act to sterilize existing anaerobic organisms and conditions that are suitable for new "emperors" have to be occurred some time during the history of Earth. The discovered low-latitude glaciations or even "Snowball" events in Proterozoic time supports the hypothesis.

While there have been many glacial events recorded in the history of the Earth, two major periods of low-latitude glaciation in the Proterozoic appear correlated with significant changes in the evolution of life and atmospheric oxygen level. The Paleoproterozoic Makganyene glaciation occurred approximately between 2.3 and 2.2 Ga, and at least two other low-latitude glaciations occurred during the Cryogenian period, between about 740 and 630 Ma. The Paleoproterozoic Snowball Earth events seem to correlate well with the appearance and flourish of oxygen photosynthetic bacteria and Neoproterozoic events are closely associated with the so-called "Cambiran explosion." The severity of these 'Snowball Earth' events is debated, but the low latitude of the glaciations indicates that, at least on the continents, ice extended to the equator, average global temperatures were likely well below freezing, and the hydrological cycle was much diminished and bioactivity largely suppressed. The rock record indicates that the atmosphere and ocean were oxygen poor until shortly before the onset of the Paleoproterozoic Snowball at ~2.3 Ga, and the weakening of the biosphere and hydrological cycle would likely have decreased atmospheric oxygen levels during the event. Low levels of peroxides and molecular oxygen generated during Archean and earliest Proterozoic non-Snowball glacial intervals could have driven the evolution of oxygen-mediating and utilizing enzymes and thereby paved the way for the eventual appearance of oxygenic photosynthesis.

Gaining insight into the origin, evolution and distribution, as well as the future of life on Earth and elsewhere in the solar system and the universe, is the primary mission of astrobiology. The combination of a hydrological cycle, chemical redox gradient, and geochemical cycle give favorable conditions for life on Enceladus. To our knowledge, these conditions are not duplicated anywhere else in our solar system except our planet. Compared to Mars, Titan, and Europa, Enceledus is the only other object in our solar system that appears to satisfy the conditions for originating life at present. Mars may have had a hydrological cycle in its early history, but there is no evidence that one exists today. Titan may be a repository of pre-biotic organic chemicals, but the conditions do not appear favorable for the development of life. Europa currently may have a hydrological cycle, but it may be a closed chemical system that will eliminate any chemical redox gradient in a geologically short time. Presently Enceladus is the most exciting object in the solar system for the search of extant life. We have compelling evidence supporting the view that Enceladus has active hydrological, chemical and geochemical cycles, which are essential ingredients for originating and sustaining life.

The possibility of duplicating the life on our planet is extremely small. All the aforementioned conditions need to be met at the right time and right place. In the recent years, the increase of greenhouse gases such as carbon dioxide and pollutants produced by anthropogenic activities strongly influences our living environment. For example, doubling carbon dioxide (occur at the end of the century) may increase the global temperature by 2-5 °C, which will greatly enhance the abundance of water vapor, which has positively feedback to the warming. If we do not pay attention to this, our planet will soon become a planet like Venus, which has surface temperature of ~700 °C.

References:

1. Chyba, C. F., and Phillips, C. B., *Origin of Life and Evolution of the Biosphere*, 2002.
2. Davies, P., *The fifth miracle*, Simon & Schuster, 1999.
3. IPCC, Climate Change: The Scientific Basis, Cambridge Univ. Press, edited by J. T. Houghton et al., 2001.
4. Liang, M. C., Hartman, H., Kopp R. E., Kirschvink, J. L., and Yung, Y. L., *Proc. Natl. Acad. Sci.*, 2006
5. Liang, M. C., Yung, Y. L., and Shemansky, D. E., *Astrophy. J. Lett.*, 2007.
6. Lunine, J. I., *Earth-Evolution of a habitable world*, Cambridge Uni. Press, 1999.
7. Parkinson, C. D., Liang, M. C., Hartman, H., Hansen, C. J., Tinetti, G., Meadows, V., Yung, Y. L., *Astron. & Astrophys.*, 2007.