EPSC Abstracts
Vol. 10, EPSC2015-5, 2015
European Planetary Science Congress 2015

Starting life requires more than organic matter

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Abstract

A physicochemical approach is proposed to study requirements for the origin of life in agreement with developments made in Systems Chemistry for several decades. Emphasis is made on the occurrence of environments generating abiotic chemical systems making more of themselves under far from equilibrium conditions. It follows that the presence of organic matter is only one of the components needed for the process of chemical evolution leading to life. The presence of an energy source with a potential equivalent to that of visible light is needed to render the activation step kinetically irreversible and the reproduction loop a unidirectional flux of reactants. This condition is required in order that reproduction follows an exponential law and dynamic kinetic stability governs the evolution toward the selection of improved variants. According to these views, no fundamental difference can be found between the chemical and biological stages of evolution.

1. Introduction

Since the early mention of a "warm little pond" by Darwin, it is usually considered that the origin of life required liquid water, organic matter, and energy. Whether components of the first living organisms could be brought about by abiotic processes or produced through an early protometabolism directly connected to the origin of life triggered a lively debate. In a further stage, the emergence of life is sometimes considered as a matter of probabilities depending on the random emergence of the first self-reproducing polymer. However, organic components of life and especially polymers being thermodynamically unstable, free energy sources must be coupled to the process in order that the components of the first living organisms assemble. Therefore, the origin of life process could have unfolded under far from equilibrium conditions in accordance with an alternative approach taking into account one of the essential features associated with life, namely disequilibrium. A subsequent issue is to determine more precisely how far from equilibrium the evolving system must be for expressing the possibility of selection of variants and further evolution towards complexity. Is there a threshold beyond which self-organization of life is possible? Or does the process simply need to be thermodynamically favorable? These questions are worth to be considered before assessing the ability of exoplanets to harbor life and its emergence.

2. Discussion

Though it gives some insight into the process through which life proceeds [1], [2], thermodynamics fails in describing the evolutionary aspects of life [3]. On the other hand, studies carried out since the seventies [4], [5] have shown the importance of replication and autocatalysis in chemical evolution. A condition for the selection of the most efficient variants through which a system can improve its dynamic kinetic stability [6], [7] lies in the occurrence of exponential growth that is only limited by the availability of reactants [8]. In agreement with the need of far from equilibrium conditions to observe self-organization through the development of dissipative structures [9], this requirement imply that the system must be fed with energy in a kinetically irreversible way. The requirement of kinetic irreversibility is associated with kinetic barriers high enough to avoid the reverse reaction corresponding to the activation step of a metabolic cycle or of a replication cycle (Figure 1). In other words, the reverse reaction must be negligible at the time scale (*i.e.* the generation time for reproduction) at which the metabolic cycle proceeds [10]. The main consequence of this requirement is that the process must not only be exergonic (correspond to a favorable free energy difference between products and reactants) but must additionally involve a cost of irreversibility corresponding to the kinetic barrier of the reverse reaction (Figure 1). This parameter corresponds to a free energy threshold that must be passed in order that a behavior analogous to natural selection is observed [10]. Temperature and the turnover time of the metabolic or replicating cycle constitute the two parameters influencing this threshold. A value of ca. 100 kJ mol^{-1} can be assessed for this threshold at ambient temperature (300 K) and for turnover time values reproducing the lifetime of living organisms on the Earth [11]. This value represents a significant part of the free energy of covalent bonds in agreement with the specific ability of carbon in forming covalent bonds with other elements. It increases rapidly with temperature making the origin of life unlikely at high temperature [12]. Taking into account the need for biochemical energy carriers, a free energy potential equivalent to that of visible light has been assessed for energy sources needed to initiate the origin of life [10], [11]. Evolution has led to molecular engines capable of taking advantage of much lower potentials but these systems were not available for simple life occurring through chemical cycles.

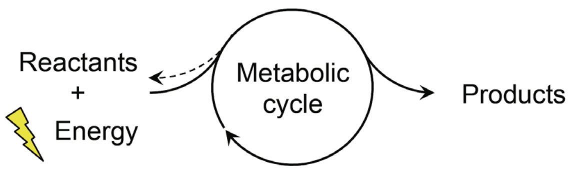

Figure 1: Kinetic irreversibility: the intermediates of a metabolic cycle must not revert to reactants (dashed arrow) within the timescale of the metabolic cycle.

6. Summary and Conclusions

A physicochemical analysis of life leads to the determination of energy requirements for the origin of life. The free energy threshold deduced from this analysis allows a selection among scenarios proposed for the origin of life. Energy sources possible for feeding rudimentary self-reproducing systems capable of evolution have thus been identified as photochemistry or other low entropy carriers. Hydrothermal systems miss the requirements in terms of chemical potential and chemical systems required for taking advantage of concentration gradients require highly sophisticated devices, the spontaneous emergence of which is in contradiction with the Second Law. This analysis is of high potential interest for determining conditions prone to the origin of life on planetary bodies.

Acknowledgements

The author thanks the COST action CM1304 “Emergence and Evolution of Complex Chemical Systems” for the opportunity of fruitful scientific interactions, the Agence Nationale de la Recherche for support (PeptiSystems project ANR-14-CE33-0020) and Prof. Addy Pross for fruitful exchanges.

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