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Origin of life — Symmetry breaking in the universe: Emergence of homochirality

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Abstract

Attempting to understand life's origin is finding a hypothetical sequence of physicochemical steps (based on distinct logical conditions) that lead to individuals with a life-like genetic apparatus. An oligomer emerges that is able to replicate. It must be homochiral to allow precise interlocking between template and growing replicate. Life evolves on the planet: symmetry breaking, emergence of homochirality.

Keywords: Origin of life; Chirality; Symmetry breaking; Molecular engineering; Self-organization

1. Introduction

The question of how life emerged has a number of different aspects that have been studied intensively in the past few years [1–4]. In one of these aspects chemical reactions have been studied that give information on what may have happened on the prebiotic planet that can be relevant to life's origin:

1) How chemical reactions on prebiotic earth might have led to precursors of biomolecules [5].
2) How replicating strands might have been arisen [6,7].
3) How the synthesis of various nucleic acids, e.g. pyranosyl-RNA, contribute in understanding early evolution [8,9••].
4) How self-organizing biochemical cycles may have developed [10].
5) How vesicles divide and multiply [11,12].
6) How early metabolism may have developed via thioester forming short polymers [13] or on two-dimensional surfaces of pyrite as autotropic origin [14,15].

In a further aspect theoretical concepts have been developed that are important in today's views on the origin of life:

1) The hypothesis that conditions to form self-organizing molecular systems in a homogeneous medium in a steady state far from equilibrium are essential in understanding the emergence of life [16] and profound investigation of principles of self-organization in that case [17••–20].
2) Double origin hypothesis: emergence of the genetic machinery within the pre-existing metabolic unit [21].
3) Hypothesis that life criteria are the presence of an individual unit, metabolism, inherent stability, information-carrying subsystem, regulated processes; potential life criteria are growth and reproduction. Minimal life: Chemoton [22].

The present paper has a different focus: Can we understand the emergence of life as a process based on physics and chemistry, i.e. can we find a distinct continuous sequence of hypothetical physicochemical steps finally leading to a bio-like genetic apparatus, the basic machinery of bio-systems? This means: can we identify, by logical considerations, the revolutionary changes in structure and functionality required to reach that goal; can we find why, by what mechanisms, these changes should occur, by what environmental influences they should be driven by chance and necessity.

Such questions lead to the particular paradigm of the present approach: First, attempt to find the logic pattern of a process

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that leads to a bio-like genetic apparatus: Try to find out by systematic thinking how that ingenious and complex machinery could have evolved in many distinct steps. Then, try to give a sequence of hypothetical steps that are based on this logic structure, on the existing chemistry and physics, and in accord with prebiotic conditions and biochemical requirements. Develop such a hypothesis to reach an increasingly reliable, realistic, detailed and experimentally supported description of the process.

Here we restrict to general aspects and give a more detailed description of only the very first hypothetical steps including the step leading to homochirality.

2. Essence of present approach

Living individuals, in the present context, are molecules or aggregates of distinctly interlocked molecules that can reproduce themselves in the given environment and evolve, as a form, in appropriate achievable environments into forms of continuously increasing complexity and functional intricacy. By what reason life emerged and evolved? Is its appearance the result of a physico-chemical process to be specified step for step?

2.1. Paradigm: search for a continuous sequence of physicochemical steps toward a life-like genetic apparatus

The requirement for living aggregates to come into being, resulting from logical considerations, should hold anywhere in the universe at appropriate locations; the chemistry can be similar to the one on the early earth, or quite different.

The question, can we model a detailed sequence of physicochemical steps that leads to individuals with a bio-like genetic apparatus, is also of principle nature. It is an attempt to answer the question: can the origin of life be understood on the basis of physics and chemistry, is it not in contradiction to thermodynamics?

A hypothetical pathway has been modeled [23••,24•–28•, 29,30•–34]. The intention was not to describe the historical pathway but to show that a reasonable pathway can actually be given (by specifying the fundamental changes in structure and functionality required to finally reach a life-like genetic apparatus, by showing that no barrier appears that is not surmountable).

Increasingly detailed theoretical modeling and efforts in experimental support would be most important to get closer to answer that fundamental question. But it is widely believed that the basic question has been answered in 1971 (called annus mirabilis [22]). The conditions of self-organization in the special case of a homogeneous phase in a steady state were studied [16] and Darwinian processes taking place under those conditions were profoundly investigated [17••–20]. The aim was finding principles of self-organization. This work of Manfred Eigen has strongly influenced and activated today's thinking on evolutionary processes. He developed, on that basis, an evolutionary biotechnology allowing to get proteins with entirely new functionalities that is of primary importance in future achievements.

Attempting to find how and why the protein-producing genetic machinery emerged requires a basically different approach proposed in 1972 and indicated above [23••]: trying to solve a distinct engineering problem, to find a pathway to a given goal, not principles of self-organization. Principle features become manifest in actually proceeding along such a pathway (Sections 3 and 7).

In searching for such a sequence of steps very particular environmental conditions had to be assumed as the driving force to reach the given goal: a distinct periodicity in time, compartmentalization and structural micro-diversity. From logical considerations discussed below, these boundary conditions appear as a general requirement in modeling the emergence of bio-systems. They are the basis to understand why and how life emerged.

In my opinion a basic assumption for life to begin is the presence of an extremely particular location where the conditions are given for the synthesis of monomers that are used as the building blocks of replicating oligomers. In the vicinity small regions are present with distinct, specific properties required to drive the self-engineering process finally leading to a genetic apparatus. The problem to be solved is a very specific engineering task, a priori in agreement with thermodynamics.

As mentioned it has been assumed that the condition for life to emerge is given by the condition for self-organization in a homogeneous phase in a steady state (to be far from equilibrium) [17••]. This is in contrast to what follows from the argumentation given above and specified in Section 3 that the complexity and distinctness of the environmental conditions is fundamental for driving the complex sequential processes leading to life's emergence.

2.2. Molecular engineering and life's origin

Seeing life's emergence as a distinct engineering process driven by most special environmental conditions, has developed from the idea that chemistry should have a new goal: the synthesis of different types of molecules, planned to interlock in a distinct manner, like the components of a machine. A machine is a functional unity designed for a given purpose.

This new topic was called "Molecular engineering" to emphasize that it is a counterpart of molecular biology. First attempts to realize molecular engineering was to construct simple prototypes of supramolecular machines and of molecular based electronic devices [35–37]. A most important step toward the aim of a molecular engineering was the invention of the scanning tunneling microscope and the atomic force microscope by Binning and Rohrer. Measuring the electric current through a single molecule of particular structure has been recently achieved [38]. It is an important step toward future molecular electronic devices. Molecular engineering (molecular electronics, nanotechnology, supramolecular chemistry initiated by Jean-Marie Lehn) is a strongly developing topic. The close relation between the search for ways to construct molecular devices and attempts to find the basic mechanisms in life's emergence should be seen as a useful guideline in future developments.

3. General conditions for life to come into being: periodicity in time, compartmentalization and structural diversity

We are looking for what is required, just from logical considerations, to stimulate a process leading to aggregates of