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From astrochemistry to prebiotic chemistry an astrobiological point of view

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Abstract

Most of the organic matter present in the Universe is formed and evolves in dense molecular clouds. During the evolution of interstellar grains, it undergoes many chemical changes (ion bombardment, UV irradiations, and thermal effect) to yield a highly complex organic matrix. The interstellar grains then form agglomerates found in small objects including the original organic matter (in comets and/or asteroids). Next to endogenously formed organic matter, these small objects can serve as reservoirs of organic matter for the development of prebiotic chemistry on the surface of Earth-like planets. This kind of chemistry only developed in environments enabling the development of chemical networks continuously fed with matter and energy with a high enough potential. This is the prelude to the emergence of biosystems as it has indeed been the case on the Earth.

1. Introduction

A living organism arranges a set of chemical processes to maintain a non-equilibrium state by exchanging matter and energy with its environment, as well as to reproduce and evolve. A large set of molecules and a given environment therefore interact to sustain a living organism. The living cannot exist and grow without chemical processes, whereas a chemical reaction can take place without the necessity of living. Chemistry can be considered as "universal." However, clues that the emergence of life is a common and inevitable phenomenon in our Galaxy have not yet been provided. Currently, the only known life form resides only on the Earth. To determine if other planetary systems could undergo a similar evolution, it seems important to trace the fate of organic matter. This will help to understand what chemical processes could be established, in which environments and from which sources of matter and energy [1]. The knowledge of this chemical evolution will provide clues about the possibility of finding other environments that may lead to the emergence of biosystems.

2. Astrochemistry: the evolution of organic matter in astrophysical environments

The chemical evolution begins in dense molecular clouds. These dense clouds (10^3 to 10^5 molecules of hydrogen per cm^3) are formed of gas and dust. These dust grains are formed of a cold core (10 to 50 K) of refractory silicates and/or carbonaceous material surrounded by a set of molecules forming an icy mantle. These interstellar ices are mostly formed of water, methanol, carbon monoxide, carbon dioxide, ammonia and organic molecules such as formaldehyde and urea. These interstellar grains are of considerable importance in the process of chemical evolution of the organic matter, because the formation of the ice allows the concentration of organic molecules at the surface of grains, which facilitates the reactivity and the chemical evolution of the original organic matrix.
In some areas, the dense molecular cloud can collapse leading to the formation of protostars. This protostar evolves and emits various types of radiation interacting with the protostellar envelope, where the grains are present. These radiations (ultra-violet, infrared...), associated with cosmic rays (energetic charged ions) alter the molecules made of interstellar simple ices, driving the organic matter towards a higher complexity. Thereafter, the altered interstellar grains are involved in the constitution of a protoplanetary disk. Depending on the grain position

relative to the proto-star, the organic matter can continue to evolve through various physical and chemical alterations that proceed along with the formation of a planetary system such as the Solar System.

3. Prebiotic chemistry: the evolution of organic matter in specific environments

Once the planetary system is stabilized, two reservoir of organic matter can be distinguished. Organic matter of exogenous source can be delivered to the surface of the terrestrial planets by the impact of comets, asteroids and interplanetary dust. Atmospheric and geochemical processes can also form organic materials endogenously.

The emergence of biochemical systems can be understood as resulting from the development of more complex chemistry under the chemical and physical conditions of the environment [2]. This transition requires the emergence of molecular entities or reaction networks able to reproduce themselves and then to take advantage of the specific kind of stability associated with things that can be replicated [3]. This kind of prebiotic chemistry could only develop in specific environments, where physical and chemical conditions can maintain a dynamic chemical networks in a far from equilibrium state by constantly feeding the system with matter and energy. This transition occurred on the early Earth but we have no indication that a tightly defined environment is required. In the mean time, there is no basis for speculations that exogenous environments rich in organic matter may also lead to an emergence of life. The presence of organic matter itself is not sufficient. As noted above, the environment must provide free energy with a potential (150 $kJ.mol^{-1}$) sufficient to enable the development of a far of equilibrium chemical network undergoing self-organization [4]. Consequently, the use of the term "prebiotic", with the meaning “closely preceding the emergence of life” to qualify these environments, should be restricted to the ones in which free energy with a high potential is present. It should not be applied to astrochemistry as a whole, unless a sufficient amount of energy is available.

4. Conclusion

The studies on the chemical evolution in astrophysical environments have demonstrated that organic matter is formed abiotically, destroyed or available everywhere in the Universe, in more or less complex forms. Carbon, hydrogen, nitrogen and oxygen tend to develop spontaneously a chemistry that is universal and not limited to the biochemistry of living organisms. However, the presence of organic matter in various astrophysical environments is not sufficient for the emergence of life. Only astrophysical environments presenting a specific set of physical and chemical conditions enabling the development of far–from-equilibrium processes will enable the self-organisation of organic matter towards the living state. For understanding where life can arise, we have to understand which environments could gather these conditions.

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