THE ORIGIN AND EVOLUTION OF EARLY LIFE

M. Rizzotti
Department of Biology, University of Padova, Italy

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Summary

According to most scientists, there are at least three necessary conditions for the origin of life: the presence of organic molecules, the availability of suitable energy, and liquid water. In the present cosmic era organic molecules are widespread in galaxies. They constitute part of the interstellar gas and dust, and part of the planets orbiting stars. They come, together with their stars, from the gravitational contraction of interstellar matter. The energy in both cases is due to radiations or high local temperatures. For the syntheses of organic molecules on the planets, land volcanoes and submersed ones may have important roles. As regards liquid water, it is a chemical reagent, so the mixtures of organic molecules in its presence are different from those of the interstellar clouds or planets without liquid water. But its main importance is its capacity to foster aggregation of organic molecules that have a hydrophobic portion. Currently, the most investigated models of precellular organic aggregates are the microspheres of proteinoids, the liposomes (or lipid vesicles), and the ribozymes (folded stretches of RNA with specific catalytic activity). In spite of the controversies over these models, the final result in each case is the same—the first cell. The crucial steps on this road are cellular translation based on the genetic code and the encapsulation into a lipid-protein membrane. The first cells are supposed to feed on organic molecules on any planet where they appear. But when the supply of organic molecules lessens, the only

biospheres to survive are those where some cells become able to synthesize their organic molecules starting from just carbon dioxide. During evolution, multicellular and differentiated organisms arise from unicellular ones, but the main step is the appearance of nucleated cells. These are not necessary to sustain a biosphere, but once they appear evolution can lead to animals and then to a technological species such as ourselves. All biospheres come to an end, sooner or later; their end can be due to either stellar or planetary catastrophes.

1. Introduction

From a chemical point of view, cells are roughly speaking aggregates of organic molecules large and small, mixed with water molecules and inorganic ions in a partially fluid state. Present day cells are thought to have derived from more primitive ones that had a roughly similar chemical composition. Virtually all contemporary scientists are agreed that the first cells derived from more primitive organic aggregates that also had a roughly similar composition and might be called pre-cellular organic aggregates. The very origin of life corresponds to the transition between a pre-cellular organic aggregate and the first cell. This transition is generally believed to have occurred in some part of the primitive hydrosphere, perhaps a transitory pond, a lagoon, a sea, or the bottom of the ocean. The modern objections that are sometimes raised against this general scientific view are either that it is a case of spontaneous generation or of order arising spontaneously out of chaos.

Ever since Francesco Redi's experiment of 1668, spontaneous generation has been repeatedly demonstrated not to occur. Redi demonstrated that fly grubs do not appear in a piece of meat if flies have no access to it. Subsequently, many scientists demonstrated that the same is true for bacteria and for viruses, and the theory of spontaneous generation is considered to be decisively falsified. According to some, the idea of a transition from a pre-cellular aggregate to the first cell is a case of spontaneous generation and thus an unscientific concept. However, the spontaneous generation of pre-modern biology was not a congruent scientific theory: it was rather a "spontaneous" popular belief, albeit one shared by most philosophers and scientists. It stated that living things were expected to originate from rotting meat, dirty straw, damp mud, and such like within a short time (for example, fly grubs emerged from rotting meat within a few days); moreover, these living things belonged to a species that was present at that historical time, and even, at the right season, in that geographic area. Oddly enough, this origin did not occur where the species was absent, and did not happen for extinct species. Nor did it occur for possible but not yet existing species. Nor it did not concern single-instance living things, regardless of their inclusion or not in any species. With our present understanding of biogeography and the history of life, nobody could accept such naïve view.

In any case, research at the molecular level has shown that even the simplest cell is so complex that it is impossible to accept a quick appearance of it from spontaneous self-assembly. Also, a single protein molecule, with its thousands of atoms in definite positions and definite interactions with the surrounding ones, is complex enough to force us to reject, from a probabilistic standpoint, its spontaneous formation from a non-cellular process. This means that, even if the brilliant experiments that repeatedly

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falsified the idea of spontaneous generation had not been carried out, that idea would have been rejected by modern biology just the same on the basis of probability reasoning. Modern biology is much more aware than that of pre-modern times of the complexity of living things and their components. The crucial point is that the origin of the first cell is by no means considered as the quick origin of an object that is already instantiated in the same place and at the same time, but as the slow evolution of a new self-replicating entity from something very similar but not yet self-replicating.

As regards the second objection, it is well known that order is unlikely to spring out of chaos. In our case, order out of chaos would mean that the first cell was an ordered object whereas the pre-cellular aggregate was a chaotic one. Nobody denies that the first cell had many ordered features, but none the pre-cellular aggregates proposed so far are by any means chaotic. They are simply less ordered, but likewise made of organic molecules, which do have a series of ordered features starting from the number and relative directions of the chemical bonds of the carbon atoms. Also the surrounding environment was by no means chaotic, as it consisted of various kinds of rocks, bodies of water, and atmospheric gases, all scattered in accordance with their physical and chemical properties and on the basis of contingent historical events. The rocks and the terrain, on land or at the bottom of the sea, consisted of crystals and amorphous minerals. Organic molecules were dispersed and aggregated both in ponds and on land. In any case, all these components, both inorganic and organic, had their own ordered features. Moreover, the small organic molecules did not bind to each other at random. Also, the large molecules did not aggregate by pure chance, as some of them tended to self-organize as a result of their own chemical properties and those of the liquid medium. Inorganic crystallization exhibits a similar phenomenon. Even the order of the first cell is not supposed to have been an all-or-nothing property, because its descendants could have increased that order by achieving a more precise replication of the genome, or by acquiring more complicated protein complexes, such as those able to perform photosynthesis.

To sum up: the two objections do not refute the scientific view; they merely distort it. The fact is, the scientific view of the transition between the non-living and the living is neither an example of spontaneous generation nor an example of order arising spontaneously out of chaos.

These debates, like most debates on the origin of life, implicitly refer to terrestrial life, but they could just as well be applied to possible life anywhere in the universe. In any case, life everywhere is thought to be instantiated in cells, and the first cell is thought to have derived from a non-living organic aggregate. In general, organic aggregates, both pre-cellular and cellular, can be considered as part of an organosphere, which is the set of all organic molecules in a given place of the universe. Organic molecules are present in virtually all places of every galaxy where temperature and density are low enough to allow the presence of molecules and where there is the carbon atom.

Organospheres and their evolution depend on cosmic evolution, while this strongly depends, in turn, on the cycles of what are, at present, its major constituent bodies, i.e. the stars. As a matter of fact, scientific research on the origin of life is increasingly investigating the conditions under which life originates, evolves, and becomes extinct in

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a cosmic context. Among these conditions, three are of the utmost importance: the presence of carbon atoms, a suitable source of energy, and liquid water. All theoretical attempts to find alternatives to these three conditions have failed, in the sense that they turned out to be unable to explain life, for one reason or another. With reference to these three conditions (sections 2, 4, 7), we will try to be as general as possible in the present scientific context, and even speculate beyond the warrant of presently available evidence.

2. The Need for Organic Molecules

Every element gives rise to some kind of chemistry; organic chemistry is that of the sixth element of the periodic table, carbon. Both in interstellar space and on some bodies that orbit stars, organic chemistry displays the greatest variety of molecules. To give a couple of examples, all the gaseous molecules with more than five atoms that have been detected in the interstellar space of galaxies are organic ones; and the Murchison meteorite that fell on Earth in 1969 showed hundreds of different organic molecules. This large variety is well known in artificial chemistry, as the organic molecules that have been synthesized in our laboratories are ten times more numerous than the molecules of all the other elements taken together. Other elements hold the records for other properties; for example, fluorine holds the record for electronegativity, the tendency to take up an electron and thus turn from electrically neutral to negatively charged. But carbon holds the record for producing the most varied molecular structures.

This record of carbon is due to a series of properties, of which three are most important. The first and second properties are shared by other elements, but they are essential to give rise to varied and complex molecular structures, and it is their combination that makes the difference. The first of the three is rather technical: it consists of the fact that the carbon atom establishes almost only covalent bonds among its chemical bonds with other atoms. The covalent bond holds together two atoms that share a pair of electrons. Fluorine, for example, can sometimes establish covalent bonds, but it is usually in the form of a negative ion, in accordance with its high electronegativity, and tends to establish ionic bonds with elements that are usually present as positive ions. However, in ionic compounds, single ions can often replace different ones with the same electric charge, so they have no stable position in the molecules. The tendency to establish ionic bonds, or another kind of bond also based on electrical attraction, called a metallic bond, rules out a large number of elements of the periodic table, in particular, all the heaviest ones, from the ability to build up a large variety of distinct molecular architectures. In contrast, the elements that tend to establish the covalent bond form molecules in which each atom has its own fixed position with respect to the others.

The second important property consists of the possibility for a carbon atom to bind more than one atom. A hydrogen atom, for example, does frequently form covalent bonds, but it can only bind one more atom, so, instead of promoting the formation of complex molecules, it promotes their simplification because it stops any growth of the molecular architecture where it binds. This is why the atmospheres of bodies where hydrogen is concentrated mainly have the other common elements, such as oxygen, nitrogen, and carbon, in the form of simple molecules which coincide with their most hydrogenated

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form, i.e., respectively (Figure. 1), water (H_2O), ammonia (NH_3) and methane (CH_4). A carbon atom can bind four more atoms, as in methane, although sometimes it only binds three or two (Figure. 1, right). If a carbon atom binds four atoms, and one of them can also bind more than one atom, the molecule can grow at least in that direction. This happens, for instance, when a carbon atom binds another carbon atom. This property is not rare among the elements that form covalent bonds. Silicon, for example, can also bind four atoms, but it lacks the third property that allows carbon to give rise to a large variety of molecules even with few atoms.

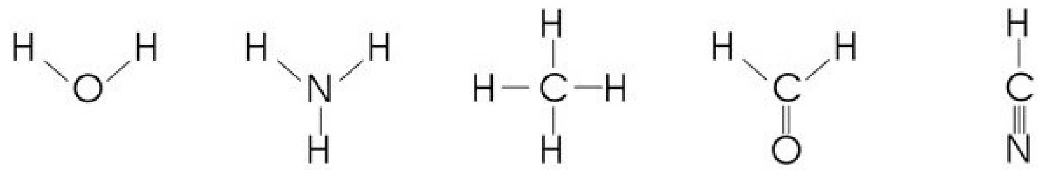

Figure. 1. Structure of five simple molecules; from left to right: water, ammonia, methane, formaldehyde, and hydrogen cyanide.

The third property, unlike the first two, is quite rare because it is a sort of coincidence. It consists of the fact that a carbon atom binds with almost the same energy to another carbon atom, to an atom of nitrogen, or to an atom of oxygen. This means that, for a carbon atom, these three possibilities are essentially indifferent. As a consequence, the variety of possible molecules increases greatly. In contrast, silicon, for example, binds oxygen with an energy that is twice as much as that with which it binds another silicon atom, so silicon is almost always bound to oxygen to give silica or silicates. There are elements that bind various different elements with similar energies: for example, this is true for many metals that form alloys. But this is because the different metals have similar properties, while carbon, nitrogen, and oxygen are very different from one another. Moreover, both nitrogen and oxygen easily bind, in turn, more than one atom, so that they, unlike hydrogen, do not stop the growth of a molecule.

Carbon has many more properties that are also interesting in determining the great variety of organic molecules. For example, the possibility of establishing two covalent bonds, instead of one, as in formaldehyde (Figure. 1), with the same atom gives rise to a rigid portion, instead of a flexible one. This is particularly important within large organic molecules such as polypeptides. The covalent bonds between two atoms can be up to three, as in hydrogen cyanide (Figure. 1, right). We may also add that carbon, nitrogen, and oxygen are the most widespread reactive elements in the universe besides hydrogen, so a complex cosmic chemistry in the form of an organosphere is an easy outcome everywhere these elements are present and molecules stable. The cosmic abundance of helium is second only to that of hydrogen, but this element is a noble gas, and does not form molecules. (In fact, a few molecules have also been formed with noble gases, but very few, and helium is more refractory than the other noble gases to giving molecules.)

Why is a great variety of molecules and molecular portions so crucial for the existence of life? The answer is that even the simplest living thing relies on rapid reactions of some particular molecules to the exclusion of others, i.e., a metabolism. The alternative

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reactions that a single molecule can undergo are many, but only one or few of them take place in the cells. These are the ones that lead to assimilation, i.e., to building of molecules similar to those already present. Otherwise, the cell does not duplicate at all. Without this selective chemistry a cell would undergo decay toward chemical equilibrium, which means the end of all reactions and, as a consequence, the end of assimilation and life. The selective chemistry based on the high speed of specific reactions requires specific catalysts, such as the cellular enzymes. The catalysts are molecules that increase the speed of spontaneous chemical reactions. If they are specific, they select the reaction to be speeded up, i.e., they select the molecules that react and the products to which they give rise. The properties involved in this selection are those that can create a complementarity with the reactants to be selected and bound for the very short time for the reaction to take place. The complementarity is based on a site of the enzyme that matches the molecules to be selected, a situation similar to that of a specific antibody that has a site that allows it to bind a precise antigen.

A binding site that is specific for a couple of reactants needs many molecular groups that are precisely located, oriented, and movable, and this can only be achieved if a molecule is complicated enough to keep these groups in the right position with the right orientation and mobility. A comparison can be made with the old-fashioned children's toy called Meccano. Suppose a child sticks different pieces with different orientations into a ball of wax and also establishes the kind and range of movement of each such piece. If the child wants to hold these pieces in the right way even after the wax has melted, he or she has to build a large scaffold with many more pieces of the Meccano that determine the constraints in orientation and motion. Similarly, to hold the chemical groups of a specific site in the right situation, a large molecular scaffold is necessary.

It is evident now that for life the true requirement is not carbon, but organic molecules. The presence of carbon is a prerequisite, but there is in addition the need for an environment that is compatible with the formation and the relative stability of organic molecules. Carbon can exist in many different physical and chemical conditions, whereas organic molecules are much more delicate. For example, the carbon atom is compatible with a wide range of temperatures, whereas most organic molecules cannot resist temperatures above 400 degrees Celsius. The stability of very complex molecules, such as enzymes, is much weaker: most of them cannot resist 100 degrees Celsius and also require a suitable aqueous medium (sections 4 and 7).

As regards possible alternatives to the carbon atom, it can be remembered that the construction of complex architectures has also been investigated for particles different from atoms. However, these exotic "molecules," in spite of their theoretical interest, are usually very unstable and at most able to give rise to a very simple "chemistry." No complex exotic molecule has resulted so far and, even less so any exotic cell. This means that no association of particles has ever been found that is able to give rise to complex microscopic objects, so the carbon atom really turns out not to be replaceable.

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Biographical Sketch

Martino Rizzotti teaches Biological Evolution at the University of Padova, Italy. His experimental research is mainly concerned in comparing the hemoglobin systems of fish groups. His theoretical research ranges from the axiomatization of genetics to the definition of life; on the latter subject he edited a book entitled *Defining life: the central problem in theoretical biology* (Univ. of Padova, 1996; www.bio.unipd.it/information/rizzotti.html). His studies on life in the universe concern precellular organic aggregates, the origin of the main cellular organelles, and the prerequisites of intelligence. In particular, he has advanced new hypotheses on the origin of the flagellum of bacterial cells and the origin of the cilium of nucleated cells. On these subjects, he has published *Early evolution: From the appearance of the first cell to the first modern organisms* (Birkäuser: Basel (2000); www.birkhauser.ch).