PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2011) **369**, 620–623
doi:10.1098/rsta.2010.0312

Review

Life as a cosmic imperative?

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The origin of life on Earth may be divided into two stages separated by the first appearance of replicable molecules, most probably of RNA. The first stage depended exclusively on chemistry. The second stage likewise involved chemistry, but with the additional participation of selection, a necessary concomitant of inevitable replication accidents. Consideration of these two processes suggests that the origin of life may have been close to obligatory under the physical–chemical conditions that prevailed at the site of its birth. Thus, an extrasolar planet in which those conditions were replicated appears as a probable site for the appearance of extra-terrestrial life.

Keywords: origin of life; natural selection; extra-terrestrial life

As a premise to this presentation, I shall take the term 'extra-terrestrial life' to refer to a form of life resembling Earth life in all its basic properties, including the DNA–RNA–protein triad, that has arisen independently on some extra-terrestrial site. This definition excludes forms of life founded on a different kind of chemistry, whose existence is purely speculative. It also excludes extra-terrestrial forms of life sharing a common origin with Earth life, no doubt a fascinating possibility, but of a different sort.

The title of this essay appeared, but without the question mark, as the subtitle of my book *Vital Dust* [1]. In that book and in others [2–4], I defended the view that life is an obligatory manifestation of matter, written into the fabric of the universe, and that there must be many sites of life, perhaps even intelligent life sometimes, in many parts of our galaxy and in others. I see no reason to change my mind on the topic, but feel that, in view of the conjectural nature of the affirmation, a question mark is in order.

Perhaps the most telling pieces of evidence we have available on the subject are the findings, initiated by the late Stanley Miller more than 50 years ago, that amino acids and other small chemical building blocks of life can be generated in the laboratory under simple conditions likely to have obtained on the prebitiotic Earth. Even more impressive are the more recent observations that such molecules arise spontaneously in many sites of our solar system, as shown by the analysis of comets and meteorites, and probably also in other parts of the universe,

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One contribution of 17 to a Discussion Meeting Issue 'The detection of extra-terrestrial life and the consequences for science and society'.

as revealed by the spectral exploration of space. Such products of cosmic chemistry most probably provided the chemical seeds of life on Earth, a view shared by many workers but not by all [5,6].

Another significant piece of evidence comes from traces, dating back more than 3.45 billion years, believed to be of fossilized micro-organisms. These were presumably preceded by an earlier form known as the LUCA, the 'last universal common ancestor' of all life on Earth. The nature of the LUCA is a hotly debated topic, but its existence leaves no doubt. It is supported by the many close similarities that have been found to exist among all living beings so far investigated and, even more demonstrative, by the many molecular phylogenies that have been established from comparative sequencing results and have revealed that all known living beings, including prokaryotes, protists, plants, fungi, animals and humans, are descendants from a single ancestral form of life.

Thus, elucidating the origin of life amounts to tracing the pathway that led from simple building blocks, most probably products of cosmic chemistry, to the LUCA. This pathway is unknown, except that it may confidently be divided into two stages separated by the first appearance of replicable molecules, most probably of RNA. Up to this event, only chemical reactions were involved. After it occurred, selection was added to chemistry.

To the extent that chemistry was involved, the processes leading to the origin of life may be viewed as obligatorily occurring under the prevailing physical–chemical conditions and imposed by those conditions. Chemistry deals with strictly deterministic, reproducible events. Let even a tiny element of chance affect chemical events, and there could not be any chemical laboratories or industries. We could not afford the risk.

Selection is different. Originally formulated by Darwin as the mechanism of evolution of reproducing living organisms, natural selection also affects replicating molecules such as RNA, as first shown by Spiegelman [7] and since repeated in a variety of ways by many investigators. In both cases, the essence of the process lies in the imperfections of reproduction. For all sorts of reasons, whenever entities are replicated, variants of the original model are inevitably produced. Selection acts on those variants to automatically bring out those that are most stable and, especially, most capable of producing progeny, under the prevailing conditions. This process is inseparable from replication itself and must have appeared at the same time as the first replicating molecules in the development of life.

Like chemistry, selection depends on environmental conditions but with a major difference. Natural selection can act only on the variants that are offered to it. A cornerstone of evolutionary theory is that the variants on which natural selection acts arise by chance factors, whether they be replication inaccuracies or other accidents. Whatever the causes of the variations (mutations) they are entirely unrelated to any sort of anticipation of future needs. Natural selection acts blindly on the products of chance. It has no foresight.

This fact has long been interpreted as indicating that natural selection is ruled by contingency (e.g. [8,9]). Gould's magnetic tape analogy has become famous: rewind the tape and let it play again, the result will be entirely different.

There is a theoretical flaw in this reasoning. The fact that an event occurs by chance does not exclude its inevitability. All depends on the number of opportunities offered by chance for the occurrence of the event, as compared with its probability. A simple calculation shows that a chance event will take place with a 99.9 per cent likelihood if it is provided a number of chances of taking place equal to approximately seven times the inverse of its probability [3,4]. Thus, even a seven-digit lottery number, with one chance in 10 million of coming out, reaches a 99.9 per cent probability of winning if 69 million draws are held. Such a possibility is of course totally unrealistic in the case of a usual lottery, but the evolutionary lottery is different. It does not depend on single draws, but operates over immense durations and involves a very large number of individuals. The enormous diversity and adaptability of the living world are proof that natural selection has, in a large number of cases, been offered enough variants by chance to approach optimization, that is, reproducibility under similar conditions [3,4].

Additional evidence for this is provided by the growing number of instances of evolutionary convergence—independently responding to the same challenges by the same adaptations—noted in recent years by evolutionists [10,11]. Investigators impressed with this fact no longer accept the 'gospel of contingency' [3] defended by their predecessors, to the point of claiming that the same outcome would probably occur if evolution were allowed to run twice [11], in direct opposition to Gould's affirmation. There are reasons to believe that molecular selection may similarly come close to optimization under sufficiently stringent constraints.

The conclusion emerging from this summary analysis is that the origin of Earth life, being dependent on deterministic chemical reactions and on frequently optimizing selection processes, must have been close to obligatory under the physical–chemical conditions that obtained at the site of its birth. This contention is further supported by the fact that a very large number of steps must have been involved. For the final outcome to have a reasonable chance of taking place, most of those steps must have had a 'reasonably high probability' ([12], p. 1034) of occurring. Otherwise, the probability of the entire succession ever coming to fruition tends to become vanishingly small [1,12].

The possibility obviously cannot be ruled out that some highly improbable chance event was included in the series, thus making the entire outcome highly improbable. For practical reasons, however, if one wishes to detect extra-terrestrial life, this possibility is best disregarded, as it would mean searching for a fluke.

If the above conclusion is accepted, it follows that the most likely cradle of extra-terrestrial life would be a planet on which the physical–chemical conditions that obtained where and when Earth life arose would be reproduced. Unfortunately, those conditions are not known, except that they must have included the presence of liquid water and the absence of molecular oxygen, a late product of life on Earth. Opinions on the topic vary greatly among experts.

Personally, I tend to rally to the view, proposed by a number of investigators, that life originated in a hot, volcanic environment, possibly similar to the abyssal hydrothermal vents that have attracted much attention in recent years. This possibility was first suggested by early bacterial phylogenies based on the comparative sequencing of 16S ribosomal RNA, which revealed that all the most ancient micro-organisms are adapted to high temperatures [13]. This argument has lost much of its value, as the ancestors of those thermophilic bacteria may have appeared long after the LUCA and may have acquired thermophily in the course of this evolutionary process. My own reasons for advocating a 'hot cradle' for life are that two substances that play a key role in biological energy transfers in all living organisms, hydrogen sulphide (in the form of thiols and thioesters) and inorganic pyrophosphate (mostly in the form of ATP and related compounds), arise spontaneously on Earth only in volcanic surroundings [3,4].

If these speculations are correct, a potential life-bearing planet would, in addition to containing liquid water and no atmospheric oxygen, have to display volcanic activity. Whether extrasolar bodies possessing these properties will ever be discovered, or, even, be technically discoverable, is not for the biologist to judge.

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