LIFE IS IN THE STARS

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To the writers and readers of science fiction, life is the material of fantasy and speculation: How did it begin? Did it just happen? Did an alien astronaut once visit Earth and leave our ancestors in his litter? Can it be made in the laboratory? If so, what Utopian or horrifying visions might it make possible? Is it to be found on other planets of other stars? If it is, what forms might it take? When we reach the farther depths of space, will we meet intelligence? Will these other beings be ones whom we can love, with whom we can talk, from whom we can learn? Or will they be the stuff of nightmares?

To the biologist and chemist, life is a phenomenon of interacting chemical reactions, and what they call a living system is characterized, like Achilles' ship, by a continual renewal of its substance. To them, life is a question to be studied in the laboratory, and though they cannot answer all the questions of the science-fiction world, they can say, "Yes, it may be possible to make life in the laboratory," and, "Life probably does exist on other worlds." Indeed, J. B. S. Haldane said in October 1963, "Some of us, or of the next generation, will try to make a living organism." He could say this because we now have a nearly complete— in principle— understanding of how life first arose on Earth. We can even justify the claim that the chemistry of the universe is such that life is inevitable wherever certain broadly defined conditions hold.

Furthermore, this inevitable life may be much like that found on Earth. The organic compounds of which our world's living systems are built consist mostly of the elements carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus, and these organo or bioelements are among the most abundant elements in the universe. However, while life may be expected to develop" around readily available materials, this does not imply that there is anything *necessarily* inevitable about "life as we know it," based upon water and oxygen and proteins. There must, after all, be worlds where water cannot be liquid and where the chemistry of life would have to be fitted to some other solvent. And even here on Earth there are a few kinds of bacteria that do not use oxygen.

What does appear to be inevitable is that wherever water can be the solvent, life will be based upon amino acids and their polymers, the proteins, for the experiments of those chemists interested in the problem of the origin of life have strongly indicated that, early in the -history of any watery planet with some energy supply, proteins will be formed in large enough quantity to support the development of life. Accordingly, we can expect that on many of the ten billion Earth-like planets estimated to lie among the billion billion planets of the hundred billion billion stars in the observable universe there is life whose chemical basis is similar to that of our own. And a few of these planets are bound to hold intelligent life.

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Although the source of life has been a goal and obsession of philosophy and religion as long as man has existed, it was not so very long ago that men believed that living animals could and did arise from dirt, slime, the sea, and rotten meat without the aid of parents. It was even thought, quite seriously, that when a sweaty shirt was put into a closed vessel with a handful of wheat grains, the vapors combined to form full-grown mice, and that lambs were formed within certain fruit. It was not until the Seventeenth Century that Francesco Redi demonstrated that maggots came from fly eggs rather than from rotten meat alone and began the debunking of the myths. Other skeptical investigators soon reduced the question of spontaneous generation to that of microorganisms, such as bacteria and molds, ruling it out for all higher forms of life.

In 1864, however, Louis Pasteur provided strong evidence that spontaneous generation did not occur at all—strong enough, in fact, to win a prize offered by the French Academy of Sciences for a solution to the argument. By drawing the neck of an ordinary round-bottomed flask out into an S-shape long enough to keep the dust in the air from drifting through the neck to a supply of nutrients in the flask, he demonstrated that even microorganisms always arise from others like themselves. Unfortunately, this was the beginning of the dogma, “Life always and only arises from life.” This “law” of nature hampered the serious investigation of the origins of life for many decades, reducing the status of any scientist who even thought of the question to that of a dilettante.

But the question was and is real. Because the Earth has not always been, there could not always have been life on Earth. So how did it get here? Arrhenius, in 1908, begged the question with the concept of panspermia, according to which life reaches any world as tiny drifting spores arising elsewhere in the universe. He ignored the question of how the first spores arose, and he failed to recognize—unlike Charles Darwin, Aleksandr I. Oparin, and others —that a necessary prerequisite of the origin of life anywhere is its absence. Darwin even went so far as to suggest that perhaps the then-current disbelief in spontaneous generation was not justified and that it might indeed occur. In an 1871 letter to a friend, he remarked,

“It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, et cetera, present, that a protein compound was chemically formed ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which could not have been the case before living creatures were formed.“

Spontaneous generation, then, might still occur, but it would not be detectable and it would scarcely matter to the world.

The question is real, and it cannot be put off by appealing either to panspermia or to the intervention of some alien astronaut. It cannot even be left in the lap of God, for divine intervention is the last resort of the ignorant, and the origin of life is a problem we can hope to ‘solve by ourselves. Indeed, scientists have been finding recently that it is possible, and even likely, that under the conditions presumed to hold on the primordial Earth, the basic chemicals of life would have been formed solely from the laws of chemistry and would then have evolved into more complex compounds which would have given rise to structures extremely reminiscent of cells.

All elements are produced by the “cooking” of hydrogen in the enormous fusion reactors we call the stars, and the physics of the fusion reactions is such that the formation of the lighter elements—the so-called bioelements—is vastly more probable than that of the heavier ones. Released into space by novae, flares, and stellar winds, these elements and a few others, such as silicon, magnesium, calcium, and iron, form the basic material from which the planets are built. These raw materials form vast clouds of gas and dust in space, and there they undergo chemical reactions which produce many compounds—including amino acids —once thought to be produced only by living things. Occasionally, as has been reported for formaldehyde, such compounds occur in concentrations as high as one thousand molecules per cubic centimeter, which, though it is only one ten-million-billionth as many molecules as there are in a cubic centimeter of air, is a high concentration indeed for the vacuum of interstellar space.

Figure 1: A very schematic representation of the primordial Earth. The atmosphere contains many gases, only a few of which are at all common today. The seas contain these same gases in solution together with many salts. The energy which drives the reactions turning these chemicals

into more complex ones, eventually leading to proteins and living cells, comes from lightning, from the sun, as light, heat, and ultraviolet, and from the Earth itself, as heat and radiation.

Accordingly, the atmosphere which enveloped the newly-formed Earth five billion years ago would have been composed of water vapor, carbon monoxide, carbon dioxide, methane, ammonia, hydrogen sulfide, sulfur dioxide, and a few of the rest of the gases derivable from the lighter elements. There would have been no oxygen at all, of course, for there would have been no plants to make it, and the air of that long-gone era would have been a noxious, toxic brew few organisms alive on Earth today could survive. Still, it was the brew which gave Earth life.

The Earth itself, as soon as it had cooled enough to have a solid crust and liquid seas, would have been very different from what it is today. There would, of course, have been no sedimentary rocks, no coal, no oil, and no fossils. The hot rains might have been acid from the volcanic fumes that filled the air. The rocks would not have been the familiar red and brown we know today; they had not yet been exposed to oxygen, and the unoxidized iron in them would have left them colored black and green. The ultraviolet light from the sun would not have been screened by ozone, for that must come from oxygen. But the seas (comforting thought!) might have been no less salty than they are now; all the salt leached by rain and groundwater from Earth's rocks since then may be well represented by the salt beds left behind by dried-up seas.

Some of the energy that entered this system can be attributed to background radiation, about three times the present value, to meteoritic shock waves, and to cosmic rays. But most of the energy would have come from the electrical discharges, the lightning, that must have thundered a stormy accompaniment to the volcanoes and earthquakes of a calming planet, from the volcanic heat and heat from the Earth's core, and from the heat and ultraviolet of the sun. These are the energies that in time transformed the chemicals of the primordial atmosphere into the life we know. And other worlds, of other stars, must share them, as they must share the interstellar starting point. If less energy is available to them, as when they circle farther from their stars, there is still no reason to think that life cannot arise on them; it must only take longer to do so, for chemical reactions are stopped only by a complete lack of energy.

How did life begin? The philosophers and the biologists phrased the question, but they were not equipped to answer it until 1913, when W. Loeb exposed mixtures of carbon monoxide, carbon dioxide, ammonia, and water to electrical discharges and obtained glycine, one of the amino acids crucial to life as we know it today. He did not perform his experiments with any intention of imitating the conditions of the primordial Earth, but his results did indicate how the first complex organic compounds could have been formed.

Not until 1953, however, was a truly close approximation to the primordial atmosphere tested. Then Stanley L. Miller, working with Harold Urey at the University of Chicago, exposed mixtures of methane, ammonia, water, and hydrogen to electrical discharges and obtained many organic compounds, including several amino acids.

Since that time, numerous experiments, using many combinations of the chemicals thought to have occurred in the non-oxidizing primordial atmosphere and all of the possible energy sources, have shown that primordial atmosphere to be capable of giving rise to most of the chemicals we now find in living things. The chemists have even found that some of the reactions that produce this wealth of pre-biotic material seem to be most fruitful when the energy source is heat and the reactions occur on or about hot dry sand or lava. When the heat is applied to solutions of the gases typical of the primordial atmosphere and various salts in water, the same reactions may occur at much lower temperatures, even well below the boiling point of water. And even though the complex organic molecules are subject to destruction by the same energies that produce them, they can survive in the deeper waters of the seas, washed out of the air and off the hot dry shores by the rains and waves, stored away from excessive heat and ultraviolet until the next reaction on the way to life.

Figure 2: A sketch of the general type of hardware used in many of the experiments performed to evaluate the potential of the presumed primordial atmosphere to produce organic material. The reaction vessel would contain a mixture of such gases as carbon monoxide, carbon dioxide, ammonia, formaldehyde, methane, ethane, hydrogen, and hydrogen sulfide. The collection vessel would contain water which would, as the experiment progressed, come to resemble a dilute broth of many of the organic compounds thought to be necessary for the formation of the first living cell. The energy applied to the reaction vessel would be heat, ultraviolet light, visible light, electrical discharges, or radiation.

The famous "dilute soup," or broth, of the early seas would thus have contained many of the elementary building blocks of life. But how were these building blocks assembled into the larger molecules of which cells are built? This question is best illuminated by the study of proteins, for though there are data bearing on the prebiotic formation of nucleic acids, fats, and carbohydrates, the polymerization of amino acids into proteins and protein-like molecules is best understood. Because of their role as enzymes in cells, proteins have been considered as essential to, and even characteristic of, life, and when the chemists began to look for "organic" chemicals arising from the primitive-Earth conditions, they focused on amino acids, which also seemed the easiest to produce.

Their efforts have resulted in the abiotic (without life) synthesis of all of the amino acids found in living things and the demonstration of a simple, plausible way in which they can be linked together, or polymerized, to form proteins. In the mid-1950s, Sidney Fox, now of the University of Miami, exposed a dry mixture of assorted amino acids to temperatures of 120 to 200°C and found that they readily polymerized. Furthermore, if phosphoric acid was added to the mixture, the polymerization would occur at temperatures as low as 60°C, and that finding made it possible to declare that this way of polymerizing amino acids was entirely consistent with our picture of the early Earth. If amino acids formed in the atmosphere or the sea were deposited on rock by rain or waves, or perhaps by the evaporation of pools, and then dried, volcanic or solar heat would have been enough to produce from them long protein-like molecules. The conditions would have been particularly suitable along volcanic shores, of which there are still many on this planet.

The product of this reaction was called "proteinoid" because of its strong resemblance to natural protein. Not only did it show many of the physical properties of protein, including a molecular size comparable to that of small protein molecules, but it also proved to nourish bacteria, be digestible by the same enzymes we use to break down protein, show weakly enzyme-like activities in a number of the reactions important to metabolism, and have a biological effect similar to that of one hormone which controls coloring in some animals. These properties were not, of course, all shared by all proteinoids, for Fox could vary the properties of the proteinoid by varying the amino acids in the initial mixture, thus changing their susceptibility or resemblance to enzymes and conferring or removing their hormonal activity.

In general, the proteinoids are strikingly reminiscent of the proteins of life. It has been said that they are "sufficiently like protein in a general sense that (they) could have served as the raw material from which the powerful and highly specific contemporary enzymes evolved," and they might have served as "multifunctional pro-toenzymes," an " 'urprotein'… possessing nonspecific properties common to all proteins" today.1* They invite one to picture the first cell as built of proteinoid, every molecule of its substance a generalized enzyme of very low efficiency. The early seas would have held most of the substances necessary for its life, and it would have processed them inefficiently, and hence slowly. But if nothing else, that first cell would have had time; it arose, after all, perhaps four billion years ago, a billion years before the first fossils of single-celled bacteria and algae appear in the rocks of the Earth. And all that it had to do in that billion years to inherit the Earth was to acquire the abilities to grow and divide and change with the generations.

1* “Quoted from p. 172 of ”Molecular Evolution and the Origin of Life,“”by S. W. Fox and K. Dose, Freeman, 1972.

But how likely is that first cell? Many object to the idea that life could be formed without a Creator, even from a complex stew of chemicals identical to those found in living cells. They argue that the odds against the right amounts of the right chemicals coming together, in the right spatial arrangements and at the same time, are just too great. However, these people make the error of thinking that the first cell had to be as complicated as modern cells. They forget that that first cell—in a world lacking a sea full of molecules identical to those within it, a sea full of “spare parts” ready for incorporation directly into the cell—would not have required much of the machinery a modern cell needs to live and-grow. They do not stop to think that in a world where the environment is so richly laden with the chemicals of life, the only difference between a cell and its environment may be that the cell is a bit of the environment walled off from the rest by a membrane. And this could be enough to begin the long road of evolution: that first cell need, only be able to reproduce itself.

Gerhard Schramm, of the Max-Planck-Institut fur Virusforschwng, has remarked, quite truthfully, that“ once there is some self-reproducing system, whether a cell or a molecule, the argument of unlikeliness of any final system just does not hold. If that initial self-reproducing system can undergo some only slightly improbable change that makes it better able to reproduce itself, then that system’s descendants will come to be more numerous than the descendants of those systems without the‘ change. A succession of such changes, each one altering the system a little and so changing the nature of what is changed, may thus lead to some virtually infinitely improbable state, such as a brain cell, a heart cell, or a parasitic amoeba.

But there are other ways than self-reproduction to explain the evolution of relatively complicated systems. A cell is not composed simply of molecules; but also of complex subsystems, some of which we call *organelles*, and the formation or evolution of a cell or any other complex system is vastly more probable if it can be built from its component parts. For the modern cell, these parts are the mitochondria, the energy-producing “engines” of the cell, the chloroplasts, which in plants trap and convert into useful form the energy of the sun, and several other structures serving specialized functions. If, eons ago, several independent cells had taken to living together as parasites or symbiotes within the cytoplasm of one of their number-a way of life which can be found today in some protozoans—then the development of the modern cell might have been hastened, as some think, when these cells became specialized to serve different essential functions of the whole. Reproducing within and with the “master” cell, they would have represented little or no load on the genetic- apparatus of that cell and would thus have freed it for higher things.

The first cell itself would have been more probable for the prior existence of the complex proteinoids and other molecules. It has been known for some time now that the electrical charges on the parts of a protein molecule can dictate its overall shape and its interactions with other molecules, and that the resulting structure can be very specific. The best examples may be the way in which collagen molecules come together to form the fibers of cartilage and tendon, and the way in which the separate molecules of the protein that makes up the coat of a virus associate to form that structure; and no other.

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The question that remains, then, is whether proteinoid molecules show these same interactive properties. And if they do, will they form anything resembling a cell?

The answer to both questions, of course, is a resounding “yes!” Sidney Fox found that if one gram of his proteinoid was dissolved in either hot or cold water, with or without other substances present, and allowed to stand, about one billion small spheres, about one micron (one millionth of a meter) in diameter, are formed. And thanks to the nature of the primordial Earth, these spheres could have been formed in great profusion every time dry proteinoid was washed off some rocky ledge by a wave or rain.

These *microspheres* are hollow, with double walls of proteinoid similar to the double membrane of a cell, and they are not-simple bubbles: not only do they readily withstand mechanical disturbances such as centrifuging, but they contain a portion of the solution of proteinoid from which they were formed. They are about the size of some bacteria, and they respond to certain stains very like the bacteria. Like cells, they show osmosis, swelling when the fluid around them is diluted and shrinking when it is concentrated.

The enzymic properties of the proteinoid are still apparent in the microspheres, so that they may even seem to carry out some of the metabolic reactions of a true cell, and if other substances are added to the proteinoid before the microspheres are formed, the similarity to a cell can be much greater. For example, if nucleic acids are added, the resulting structure will incorporate amino acid compounds much like one key part of the cellular machinery, the ribosome, a structure of protein and nucleic acid which guides the formation of proteins from just such compounds.

Microspheres do not, of course, contain anything like the genes which allow modern cells to change with the generations, but they will divide. If the acidity of the solution containing them, or the pressure, is changed, they will split into two microspheres of approximately equal size. If they are left standing in their solutions of proteinoid, they will, like yeast cells, form small buds which enlarge, split off from their parent, and grow by absorbing proteinoid from the solution. The former method of division follows certain physical laws which are also followed by modern cells, but only the latter method has been shown to go on for several generations; and there is no reason not to expect the process, if there is a good supply of proteinoid, to go on forever.

The microsphere is thus a good model of the first cell, or protocell, but it is not so only because’it is a hollow sphere with a membrane similar to that of a cell. Nor is it a good model only because it shows cell-like activities, such as something resembling metabolism and cell division. What does make it so promising is that every time a microsphere is formed, a little bit of the surrounding solution, of the dilute broth of the primordial sea, is trapped inside it. And that bit of broth may contain any or all of the , various chemicals which are found in cells today. A microsphere could thus be formed with a little nucleic acid able to replicate itself, perhaps with a little help from the proteinoid of the microsphere, or with a molecule similar to chlorophyll that would enable it to use the energy of the sun without having to wait for that energy to transform the simple chemicals of the atmosphere into more proteinoid.

Furthermore, every accident of nature that resulted in even one microsphere being formed would result in literally billions of them. And each one would be a separate “experiment” at making a cell. There is thus little reason to wonder that the virtually infinite number of tries over the eons resulted in a cell. If life was possible at all, it was all but inevitable.

But even with the inclusion of nucleic acids and chlorophyll, the microsphere is not yet a cell. If we recall the definition of life given at the beginning of this article, as a phenomenon of interacting chemical reactions, we can see that the microsphere does not fit. The chemical reactions upon which its existence depends all occur in the outside environment. The microsphere exists only because the structural material it uses for growth can be drawn from the seas around it. To, “live” it must have some way of trapping energy, either from light or from other chemical compounds; some way of making its own proteins and other compounds, and some way of passing on its “blueprint” to succeeding generations.

All of these could have been attained in time. Once there is a microsphere that can reproduce itself, as by budding, everything becomes possible. That first microsphere includes a bit of its environment; its buds contain fractions of that bit; and the buds grow by drawing proteinoid from the sea around them and incorporating other molecules either into their structures or into the fluid within them.

Outlines of the subsequent evolution of microsphere into cell range from vague discussions of how the environment, proteinoids, and nucleic acids might have interacted in a molecular analogy of learning, which might later have somehow become true genetic heredity, to relatively frank confessions of ignorance. The development of a protocell from a protoprotein is now understood— it can be demonstrated— but the development of the modern cell from the protocell, the microsphere, is shrouded in mystery. The greatest stumbling block is the question of; how the nucleic acid genetic system was developed for though there are indications that nucleic, acids can also be formed under primitive-Earth conditions, only nucleic acids extracted from modern cells have been combined with microspheres, with the suggestive results previously noted. We can only suppose that the first combination of a protocell and a "gene" was the result of chance. Perhaps one of the stray molecules incorporated out of the environment and into some ancestral microsphere's interior fluid was a nucleic acid molecule.

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To become a true cell, however, to lead to rats and cats and oak trees and men, that nucleic acid molecule must have been able to dictate the construction of a protein molecule that could help it reproduce itself, much as certain enzymes— the polymerases— help the nucleic acids of modern cells reproduce. Such a fortuitous combination must be rare, whether in prehistory or a test-tube, but given that nucleic acids were there and that microspheres did exist in vast profusion, it must have happened. And while such a nucleic acid may not be linked to the life of its microsphere by anything , more than its inclusion, it and its protein partner will be passed on through all succeeding generations of microspheres. It will be subject to mutation, and it may thus become several different nucleic acids, each one dictating the construction of a different protein and each one helped to reproduce by the original protein. Some of these proteins will be better enzymes than the proteinoid molecules, and as the microsphere's proteinoid molecules, collected from the environment, are replaced by "homegrown" proteins, the microsphere will become more nearly a cell. Its structure will become linked to the nucleic acids it carries, and when one such cell acquires some way of trapping energy, it will be independent of the primordial environment. It will no longer have to rely on the availability of "ready-made" complex molecules. It will be able to make its own from simpler materials, and it may even do so by breaking down the amino acids and proteinoids around it to get the basic building blocks it needs. It is at this point that Darwin's observation of what would happen "in some warm little pond" becomes true; the origin of life is no longer possible..

Laboratory experiments have thus shown how life might plausibly have arisen on Earth. With waves and tides and hot rocks and solar evaporation to concentrate the amino acids and proteinoids found in the seas and to turn them into the precursors of life, with lightning and heat and radiation and ultraviolet light to turn simple molecules into more complex ones, with the physics and chemistry of the universe itself to produce the necessary elements and simple compounds in appropriate amounts, it may even be said that life on Earth was inevitable, that it had to appear as soon as a microsphere was formed with just the right bit of nucleic acid within itself.

The experiments also strongly indicate that we are not alone. If life was inevitable on Earth, then how much less so can it be on other worlds? If a planet is large enough not to lose its atmosphere and the necessary initial materials, if it has enough of an energy supply, from sun or internal heat or radiation, if it has time enough, then life may be inevitable there, too. In fact, we are now waiting for our probes to reach Jupiter and report back on the presence of the molecules, and the possibility, of life there.

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The dreams of the science-fiction writers are not only dreams. We have already made in the laboratory something that must have preceded life here on Earth; it may not be long before we actually make a cell. We can predict that life, and even intelligent life, will be found on other worlds. We can predict that its chemical basis will be similar to ours, at least if its planet of origin is at all similar to Earth. We cannot, however, predict its appearance, for there does not appear to be anything inevitable about our anatomy.

Nor can we predict its temper, its goals, its motivations. When we reach the stars, we may meet friends and allies. We may increase our knowledge, our experience, and the variety of our lives. Or we may meet our nightmares.

Whatever happens, the effects on our history and culture will be profound. “Life in a test-tube” has been called sacrilege when it was only a fetus brought to life outside the womb. What will be the reactions of the fundamentalists to a cell that did not come directly from the hand of God? How will they respond if the scientists can evolve that cell and its descendants into plants and animals and, perhaps, intelligent beings? And what will happen to racism and prejudice when the “different” are of no relationship whatsoever to man? Will it increase beyond measure as we turn our hate and fear on our creations and neighbors? Or will it vanish entirely as the greater contrasts with new intelligences, with new and wonderful faces and colorsand body shapes, with “stranger” stranger, throw our weaknesses into our awareness?

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