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THE ORIGIN OF LIFE IN THE UNIVERSE

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In the 1958 Reith Lectures, A.C.B. Lovell, Professor of Radio-astronomy of the University of Manchester and Director of the Jodrell Bank Experimental Station, described the problem of the origin of the universe as the greatest challenge the human intellect has ever faced. Along with the problem of the origin of the universe, the question of the origin of life and the origin of intelligence may be regarded as the three most fundamental questions of all science. It is my purpose this morning to outline how modern science is endeavouring to find a solution to the problem of the origin of life.

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While the problem of the origin of the universe is staggering to the human mind in its very concept, the solution to the problem may come from a surprisingly simple, one-shot observation or experiment. The theory based on the evolutionary model of a universe arising from Abbe Lemaitre's primeval atom will stand or fall when an astronomer's penetrating gaze has compared the spatial density of galaxies fifty million light years ago with those of ten billion light years ago. The rival cosmological concept of continuous creation demands the appearance

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of hydrogen at several billion trillion tons per second in the observable universe. This concept will be satisfactorily proved when a nuclear physicist can demonstrate that energy can be converted into hydrogen at the rate of one atom per year, in a volume as big as a New York skyscraper.

Author

When we contemplate the origin of life, the enormity of the problem is equalled only by the complexity of the possible solutions. "The evolution movement," wrote Bergson, "would be a simple one, and we should soon be able to determine its direction if life had described a single course like that of a solid ball shot from a cannon. But it proceeds rather like a shell, which suddenly bursts into fragments, which fragments, being themselves shells, burst in their turn into fragments, destined to burst again, and so on for a time incommensurably long. We perceive only what is nearest to us, namely the scattered movements of the pulverized explosions. From them we have to go back, stage by stage, to the original movement."

Even the formulation of this problem is perhaps beyond the reach of any one scientist, for such a scientist would have to be at the same time a competent mathematician, a physicist, and experienced organic chemist. He should have a very extensive knowledge of geology, geophysics, and geochemistry and, besides all this, be absolutely at home in all biological disciplines. Sooner or later, this task would have to be given to groups representing all these faculties and working closely together theoretically as well as experimentally. Such was the view professed by Bernal in 1949. However, today we have reason to be more optimistic. For the first time in human history, the sciences which arose as separate disciplines are seen fused together, and our own generation has witnessed the birth of such sciences as biophysics and molecular biology.

Three factors have made the scientific approach to the question "how did life begin" possible, not only theoretically but also experimentally:

a) astronomical discoveries of the century

b) the triumph of Darwinian evolution

c) recent biochemical advances.

The humanist may be indignant that a problem so profound should be regarded as belonging to the laboratory, but the experimental scientist is optimistic that his investigations will some day unravel this great mystery.

The astronomical discoveries of the century have relegated our earth to the corner of a universe made up of billions of stars. The study of the heavens, by present-day telescopes, has revealed more than 10^{20} stars. Like our own sun, each one of these stars can provide the photochemical basis for plant and animal life. Two factors become abundantly clear: that there is nothing unique about our sun which is the mainstay of life on this planet, and that there are more than 10^{20} opportunities for the existence of life. In the light of numerous possible restrictive conditions, a conservative estimate made by Harlow Shapley shows that there must be at least 10^8 planetary systems suitable for life. The astronomer, Su-shu Huang, however, considers that five per cent of all stars can support life: there are 10^{18} possible sites for the existence of life. In the light of these considerations, the question of the origin of life assumes cosmic proportions.

This conclusion which astronomers have reached by the rigorous analysis of scientific observations was already prophetically described by the Italian, Giordano Bruno, in the 16th century: "Sky, universe, all-embracing ether, and immeasurable space alive with movement -- all these are of one nature. In space there are countless constellations, suns, and planets; we see only the suns because they give light; the planets remain invisible, for they are small and dark. There are also numberless earths circling around their suns, no worse and no less inhabited than this globe of ours. For no reasonable mind can assume that heavenly bodies which may be far more magnificent than ours would not bear upon them creatures similar or even superior to those upon our human Earth."

The Space Science Board of the U.S. National Academy of Sciences in an authoritative document set the search for extraterrestrial life as the prime goal of space biology: "It is not since Darwin and, before him, Copernicus, that science has had the opportunity for so great an impact on the understanding of man. The scientific question at stake in exobiology is the most exciting, challenging, and profound issue not only of the century but of the whole naturalistic movement that has characterized the history of western thought for over three hundred years. If there is life on Mars, and if we can demonstrate its independent origin, then we shall have a heartening answer to the question of improbability and uniqueness in the origin of life. Arising twice in a single planetary system, it must surely occur abundantly elsewhere in the staggering number of comparable planetary systems.

If pursued thoroughly, this search for life elsewhere will inevitably demand that man must get into space himself. We shall, of course, get on with the job using remotely controlled life-detection systems even before this venture is fully possible. But we shall never be satisfied with negative results from our instrumental life-detectors because they are intrinsically hampered in their scope by our current ignorance of the nature of whatever extraterrestrial life there may be. Furthermore, should these preliminary sallies give positive results, the urgency for man to get there will only increase. Therefore, while the intellectual appeal of the extraterrestrial life question stands out above all else in space biology, it seems inevitable that the size of the man-in-space project (in terms of dollars and manpower) will exceed that of all other aspects of space biology."

There is a distinct possibility of our finding an answer to the question of the existence of life in our own planetary system, by an inspection of the planets with our immediate or remote sensors. Outside our planetary system one way by which we can answer the question is by making radio contact with other civilizations in outer space. The odds against success in such an attempt are literally astronomical. "There is one race of men; one race of gods; both have breath of life from a single mother. But sundered power holds us divided, so that one is nothing, while for the other the brazen sky is established their sure citadel forever" wrote Pindar in the sixth Nemean Ode.

However, we have yet another possibility in the experimental approach to the problem. As the laws of chemistry and physics are universal, the retracing of the stages by which life appeared on earth would give strong support to the theory of its existence elsewhere in the universe. Laboratory experiments on earth can reveal which materials and conditions available in the universe might give rise to chemical components and structural or behavioral attributes of life as we know it.

The Darwinian theory of evolution has postulated the unity of the earth's entire biosphere. According to Darwin, the higher forms of life evolved from the lower over a very extended period in the life of this planet. Fossil analysis has shown that the oldest known forms of living systems may be about two billion years old. Life, indeed, had a beginning on this planet. Geochemical data tells us that the earth is about four and one-half billion years old. A question immediately arises as to the history of our own planet between its birth four and one-half billion years ago and the emergence of life. This idea was uppermost in the mind of the physicist Tyndall, when in 1871 he wrote in his "Fragments of Science for unscientific people":

"Darwin placed at the root of life a primordial germ, from which he conceived that the amazing richness and variety of the life now upon the earth's surface might have been deduced. If this hypothesis were true, it would not be final. The human imagination would infallibly look beyond the germ and, however hopeless the attempt, would enquire into the history of its genesis .... A desire immediately arises to connect the present life of our planet with the past. We wish to know something of our remotest ancestry .... Does life belong to what we know as matter, or is it an independent principle inserted into matter at some suitable epoch, when the physical conditions became such as to permit of the development of life?" The consideration of biological evolution thus leads us logically to another form of evolution, namely, chemical evolution.

Recent biochemical discoveries have underlined the remarkable unity of living matter. In all living organisms, from the smallest microbe to the largest mammal, there are two basic molecules. Their interaction appears to result in that unique property of matter which is generally described by the word "life". These two molecules are the nucleic acids and protein. While each one of these molecules is complex in form, the units comprising them are few in number. The nucleic acid molecule consists of nucleotides strung together like beads along a chain. The nucleotides, in turn, are made up of a purine or pyrimidine base, a sugar, and a phosphate. In the protein molecule, twenty amino acids link up with one another to give the macromolecule. A study of the composition of living matter thus leads us to the inescapable conclusion that all living organisms must have had some common chemical ancestry. A form of evolution purely chemical in nature must of necessity have preceded biological evolution.

The evidence which is available from practically every field of science, thus leads us to the idea that nature is a unity which can be divided into categories merely for human convenience. The division of matter into living and non-living is perhaps an artificial one, which is convenient for distinguishing such extreme cases as a man and a rock, but would be quite inappropriate when describing a virus particle. Indeed, the crystallization of a virus by Wendell Stanley almost thirty years ago precipitated the need for revising our definition of the terms "life" and "living". These sentiments were powerfully expressed by Pirie in an essay entitled "The Meaninglessness of the Terms Life and Living". He compares our use of the terms "living" and"non-living" to the words acid and base as used in chemistry. While sodium hydroxide is distinctly alkaline, sulfuric acid is a powerful acid. However, in between, there is a whole variation in strength. The chemist has overcome the confusion arising from the use of the two terms, acid and base, by inventing the nomenclature of "hydrogen-ion concentration". He is thus able to describe all the observed phenomena in terms of one quantity. Thus, a liquid may have a pH of 4 or a pH of 8. We may have to invent a similar quantity in order to avoid any vagueness that might arise in applying the term "life" to borderline cases such as the virus.

Chemical evolution may be considered to have taken place in three stages: From inorganic chemistry to organic chemistry, and from organic chemistry to biological chemistry. The first stage of chemical evolution perhaps began with the very origin of matter. In a series of cataclysmic reactions during the birth of a star, the elements of the periodic table must have been formed. About 15 billion years later, when the solar system was being formed, the highly reactive elements which occur in living organisms, probably existed in combination with hydrogen - carbon as methane, nitrogen as ammonia, and oxygen as water. Four and a half billion years ago, when the planet earth was being born from the primitive dust cloud, the rudimentary molecules, which were the forerunners of the complex biological polymers of today, were perhaps already in existence. Within this framework, life appears to be a special property of matter, a property which arose at a particular period in the existence of our planet and which resulted from its orderly development.

The idea of life arising from non-life, or the theory of spontaneous generation, had been accepted for centuries. One had only to accept the evidence of the senses, though the ancients: worms from mud, maggots from decaying meat, and mice from old linen. Aristotle had propounded the doctrine of spontaneous generation in his "Metaphysics". He had traced the generation of fireflies to morning dew and the birth of mice to moist soil. His teaching was accepted by the long line of Western thinkers who had turned to him as the final authority in matters metaphysical and physical.

The ancient Hindu scriptures described life as having originated from non-living matter. The Rig Veda, for example, pointed to the beginning of life from the primary elements, while the Atharva Veda postulated the oceans as the cradle of all life.

Newton, Harvey, Descartes, van Helmont, all accepted the idea of spontaneous generation without serious question. Even the English Jesuit, John Tuberville Needham, could subscribe to this view, for Genesis tells not that God created plants and animals directly but that he bade the earth and waters to bring them forth.

The world's literature is full of allusions to this popular belief in spontaneous generation. Virgil in his "Georgics" tells us how a swarm of bees arose from the carcase of a calf. Lucretius in "De Natura Rerum" refers to the earth as the mother of all living things. "With right

It followeth then that earth hath won the name

Of Mother, since from earth have all things sprung."

Recall "Antony and Cleopatra", Act II, Scene VII, where Lepidus tells Mark Antony "Your serpent of Egypt is bred ... now of your mud by the operation of your sun - so is your crocodile."

In the middle of the last century, Pasteur, by a series of brilliant experiments demonstrated that living systems could not arise out of non-living material. Pasteur dealt the death blow to the theory of spontaneous generation which was based on incompetent observation and the willingness to accept the superficial evidence of the senses.

Unfortunately, Pasteur's work gave rise to the misconception that the problem of the origin of life could not be approached by scientific methods. The question of life's beginning was, therefore, considered to be unworthy of the attention of any serious scientific investigator. But a little thought makes it transparently clear that what Pasteur disapproved was the growth of microorganisms from sterile starting material. It is indeed a very different thing from what we are concerned with in chemical evolution - the gradual formation of organic compounds over hundreds of millions of years and the slow emergence of replicating systems.

The story of Louis Pasteur is often told to beginning students in biology as a triumph of reason over mysticism. But today we know it is perhaps the contrary. The reasonable view is to believe in spontaneous generation though in a restricted sense.

Among those who speculated on the conditions necessary for the origin of life, Charles Darwin was a pioneer. In a letter to a friend he wrote: "If we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc. present that a proteine compound was chemically formed ready to undergo still more complex changes." This was too outrageous a declaration for the conservative thinking of Darwin's contemporaries. At the height of the controversey over the origin of the species, little or no attention was paid to the remote question of the origin of life.

The great impetus, however, to the experimental study of the origin of life began with the Russian biochemist, Oparin. Already in 1924, a preliminary booklet was published by him in Russian pointing out "that there was no fundamental difference between a living organism and brute matter. The complex combination of manifestations and properties so characteristic of life must have arisen in the process of the evolution of matter." According to Oparin, "at first there were the simple solutions of organic substances whose behaviour was governed by the properties of their component atoms and the arrangement of these atoms in the molecular structure. But gradually, as a result of growth, and increasing complexity of the molecules, new properties have come into being and a new colloidal chemical order was imposed on the more simple organic chemical relations. These newer properties were determined by the spatial arrangement and mutual relationship of the molecules. In this process biological orderliness already comes into prominence."

Independently of Oparin, Haldane in 1928 had speculated on the early conditions suitable for the emergence of terrestrial life. "When ultraviolet light acts on a mixture of water, carbon dioxide and ammonia, a variety of organic substances are made, including sugars, and apparently some of the materials from which proteins are built up. Before the origin of life they must have accumulated until the primitive oceans reached the constituency of a hot dilute soup."

Twenty years after the appearance of Haldane's paper, Bernal of the University of London theorized before the British Physical Society in a lecture entitled "The Physical Basis of Life." "Condensations and dehydrogenations are bound to lead to increasingly unsaturated substances, and ultimately to simple and possibly even to condensed ring structures, almost certainly containing nitrogen, such as the pyrimidines and purines. The appearance of such molecules makes possible still further syntheses. The concentration of products is an absolute necessity for any further evolution. One method of concentration would of course take place in lagoons and pools which are bound to have fringed all early coastlines, produced by the same physical factors of wind and wave that produce them today. A much more favourable condition for concentration, and one which must certainly have taken place on a very large scale, is that of adsorption in fine clay deposits. It is therefore certain that the primary photochemical products would be so adsorbed, and during the movement of the clay might easily be held blocked from further possibly destructive transformations. In this way relatively large concentrations of molecules could be formed."

A starting point for any consideration of the origin of life must turn round the question of the cosmic distribution of elements. Astronomical spectroscopy reveals that with surprising uniformity the most abundant elements in our galaxy are, in the order of rank, hydrogen, helium, oxygen, nitrogen, and carbon. Hydrogen, oxygen, nitrogen, and carbon are indeed the basic constituents of living systems. The table on the composition of the sun illustrates the distribution of these elements very clearly. (Figure 1)

The present rarity of the terrestrial noble gases with respect to their cosmic distribution indicates that a primary atmosphere of the earth was almost completely lost in early times, and that the present atmosphere is of secondary origin. The chemical composition of the secondary atmosphere must at first have been very similar to that of the primary atmosphere. Because of its high rate of escape, most of the free hydrogen must have been lost and the principal constituents of the atmosphere must have been water vapor, ammonia, and methane. It is this atmosphere of water vapor, methane, ammonia, and small amounts of hydrogen which will be considered in this discussion as the primitive atmosphere of the earth.

The energies available for the synthesis of organic compounds under primitive earth conditions are ultraviolet light from the sun, electric discharges, ionizing radiation, and heat. It is evident that sunlight was the principal source of energy. Photochemical reactions would have taken place in the upper atmosphere and the products transferred by convection. Next in importance as a source of energy are electric discharges such as lightning and corona discharges from pointed objects. These occur close to the earth's surface and hence would more efficiently deposit the reaction products in the primitive oceans. A certain amount of energy was also available from the disintegration of uranium, thorium, and potassium 40. While some of this energy may have been expended on the solid material such as rocks, a certain proportion of it was available in the oceans and the atmosphere. Heat from volcanoes may also have been effective. In comparison to the energy from the sun and electric discharges, this was, perhaps, not too widely distributed and its effect may have been only local, on the sides of volcanoes for example.

Most of these forms of energy have been used in the laboratory for the synthesis of organic molecules. Simulation experiments have been devised to study the effect of ionizing radiation, electric discharges, heat, and ultraviolet light on the assumed early atmosphere of the earth. The analysis of the end products has often yielded, very surprisingly, the very compounds which we consider today as important for living systems.

Among the first experiments specifically designed to test some of the theories on the origin of life were those of Calvin and his associates in Berkeley. In 1951 they radiated water and carbon dioxide in the Berkeley cyclotron and obtained appreciable yields of formaldehyde and formic acid. Although in this experiment carbon dioxide was used as the source of carbon, instead of methane, it established very clearly that materials of biological significance can be synthesized non-biologically. It may be pertinent here to recall that in 1829 Wohler synthesized urea from ammonium cyanide and disproved the theory long held by Berzelius and others that a "vital force" was necessary for the production of organic compounds.

A classic experiment in this field was performed in 1953 by Stanley Miller who was then a graduate student of Harold Urey at the University of Chicago. When methane, ammonia, water and hydrogen were subjected to a high frequency electric discharge, some amino acids were produced. A more complete analysis showed a variety of organic products.

Miller's experiments on the mechanism of the synthesis of amino acids by electric discharges, indicated that a special set of conditions was not required to obtain amino acids. Any process or combination of processes that yielded the two very basic carbon compounds, formaldehyde and hydrogen cyanide, would have contributed to the accumulation of amino acids in the oceans of the primitive earth. Therefore, whether the aldehyde and hydrogen cyanide came from ultraviolet light or from electric discharges is not of fundamental importance, since both processes would have contributed to the amino acid content. It may be that electric discharges were the principal sources of hydrogen cyanide and that ultraviolet light was the principal source of aldehyde, and that the two processes complimented each other.

The work of Sidney Fox of Florida State University has centered around the thermal model of biochemical origins. Although this model limits itself to a single form of energy, a somewhat coherent picture seems to emerge.

When a mixture of methane, ammonia, and water in the gas phase is passed through a heated tube containing alumina at about 1000° and the reactants absorbed in water, amino acids are formed. Fourteen of the amino acids which commonly occur in protein have been synthesized by this method.

If the eighteen amino acids usually present in proteins are heated to about 200° C polymers can be obtained. These random polymers have been described as proteinoids. When hot saturated solutions of these polymers are allowed to cool, huge numbers of uniform, microscopic, relatively firm and elastic spherules separate. These are usually 1.5 to 3 microns in diameter. For each milligram of solid, approximately 10^7 to 10^8 microspheres can be formed. Fox's work had thus led him to a theory of the origin of organized units. He considers them suitable models for the evolution of the cell.

In the experiments in our own laboratory we have adopted the simple working hypothesis that the molecules which are fundamental now were fundamental at the time of the origin of life. We are analyzing "the primordial soup" described by Haldane. The various forms of energy which are thought to have been present in the primitive earth have been used by us in a series of experiments.

In the experiments with methane, ammonia, and water, electron irradiation was used as a convenient source of ionizing radiation simulating the K^{40} on the primitive earth. The results of this investigation clearly establish adenine as a product of the irradiation of methane, ammonia, and water. It is the single largest non-volatile compound produced. The apparent preference for adenine synthesis may be related to adenine's multiple roles in biological systems. Not only is it a constituent of both the nucleic acids DNA and RNA but it is also a unit of many important cofactors. (Figure 2)

The apparatus used for studying the effect of electric discharges on a primitive atmosphere is illustrated in Figure 3. In a typical run of 150 hours 65% of the methane was converted into organic material which could be recovered in ether and water solution. In the water soluble fraction, adenine was identified.

As formaldehyde is formed by the action of electric discharges or ionizing radiation on a mixture of primitive gases, it was used as the starting material for synthesis in a further series of experiments. A preliminary separation into groups of sugars seems to indicate that by far the highest yield is of the pentoses and hexoses. Among these, ribose and deoxyribose, the two sugars present in RNA and DNA were identified.

In a third series of experiments, hydrogen cyanide was used as the starting material. This, again, is one of the primary products when a mixture of methane, ammonia, and water is exposed to electric discharges or ionizing radiation.

The use of hydrogen cyanide as starting material is also strengthened by the theory that comets may have been responsible for the accumulation of relatively large amounts of carbon compounds on the primitive earth. The CN band is generally the first molecular emission to appear on the tails of comets during the travel of these bodies towards the sun. It is also the band with the largest degree of extension into the comets' heads. It is possible that the heads of comets contain frozen free radicals which are volatilized by radiant heat from the sun. It is also possible that they contain frozen molecules which are vaporized and photodissociated into radicals by solar radiation.

About 40 million comets are now reckoned to be present in the solar system, and it has been calculated that about 100 comets have collided with the earth since the formation of our planet some 5×10^9 years ago. The amount of cometary material trapped by the earth during its first two billion years can be calculated to be about a thousand billion tons. Most of the cometary material must have been retained by the magnetic and gravitational fields of the earth. Hydrogen cyanide or its reaction products may thus have been found in fairly large concentrations either locally or distributed through the earth's primitive atmosphere.

When hydrogen cyanide is exposed to ultraviolet light a large number of organic molecules are formed. Among these we have identified adenine and guanine, which are constituents of the nucleic acid molecule.

In the experiments already described we have established the formation of the purines adenine and guanine and the sugars ribose and deoxyribose. It was therefore of interest to see whether the same sources of energy which were responsible for the synthesis of the purines and sugars could be instrumental in the synthesis of nucleosides and nucleoside phosphates leading up to the synthesis of the energy source adenosine triphosphate.

It has been suggested that the earth's primitive reducing atmosphere was at least slightly transparent around 2600 Å and that the activation of purines and pyrimidines by ultraviolet light in this region was a possible step in the formation of nucleosides and nucleotides. In our laboratory we have satisfactorily duplicated these conditions and established the synthesis of adenosine, adenosine monophosphate, the diphosphate and ATP the energy source of all living systems.

Recent developments in the science of quantum biochemistry has thrown new light on some very significant aspects of chemical evolution. It is a striking fact that many of the molecules which are essential to living systems are conjugated systems exhibiting the phenomenon electronic delocalization. In the nucleic acids, for example, the purines and pyrimidines are conjugated systems. Although the proteins do not, at first sight, appear to enjoy this property, a closer look shows us that the matrix of hydrogen bonding which exists in a protein molecule provides a certain measure of electronic delocalization. In the high energy phosphates, there is interaction between the mobile electrons of one phosphoryl group with those of another. The porphyrins, for example chlorophyll and haem, which are of paramount importance in living systems are highly conjugated molecules.

Even this meager consideration of electron delocalization leads us to the following conclusions:

(a) Evolutionary selection used the most stable compounds.

(b) On account of electron delocalization these compounds were best adapted for biological purposes.

(c) The possibility of life as we know it was made more probable by the appearance of these compounds.

The choice of conjugated systems is perhaps the most important quantum chemical effect in biochemical evolution.

Carbon and silicon appear in the same group of the periodic table and both need 4 electrons to reach the configuration of the nearest inert gas. On account of this superficial and apparent similarity between carbon and silicon the question of a "silicon biology" has often been raised in discussions on the origin of life. However, a careful consideration seems to indicate that such a prospect is very unlikely.

One answer to the question is forthcoming from a consideration of cosmic abundance. Carbon is certainly more prevalent than silicon in the universe. Another reason arises from the fact that hydrogen, carbon, nitrogen, and oxygen have been utilized in living systems, since they are the smallest elements in the periodic table and can achieve the stability of inert gases by the addition of 1, 2, 3, and 4 electrons. Small atoms form tight and stable molecules. They can also form multiple bonds. In comparison to carbon, silicon forms weaker bonds with itself and other atoms. Silicon does not form multiple bonds, and the result is the formation of large polymers, like quartz, which are unwieldy and also remove any available silicon from circulation. A further reason for the unsuitability of silicon for life processes arises from the fact that silicon compounds are fairly unstable in the presence of water or oxygen.

Optical activity has often been suggested as a very distinctive characteristic of molecules present in living systems. In living organisms all syntheses and degradations involve only one enantiomorph.

Molecules are either left handed or right handed. While a start with one form or the other would have been self-perpetuating, it is difficult to understand how the initial choice was made. Physical forces such as circularly polarized light, the surface of asymmetric crystals, or spontaneous crystallization can not account for the overwhelming tendency to produce only one form rather than the other.

A reasonable explanation appears to be that the structural demands of large molecules required the use of one form rather than both. The use of one optical isomer rather than mixtures would undoubtedly confer great stability on the polymers. This still does not answer the question of how the initial choice was made. Professor Wald describes how he once discussed this matter with Einstein, and this was Einstein's reply: "You know, I used to wonder how it comes about that the electron is negative. Negative - positive - these are perfectly symmetric in physics. There is no reason whatever to prefer one to the other. Then why is the electron negative? I thought about this a long time, and at last all I could think was: it won in the fight!"

The most plausible solution appears to be that the single optical isomers were selected on the basis of stability of the structures of higher order. The final choice was arbitrary. This is a case of natural selection at the molecular level. It accords with the evolutionary scheme: "we are the products of editing rather than authorship." It will be most interesting indeed if the sampling of martian life reveals the presence of d - amino acids rather than l - amino acids. If we were to sample all life in the universe we should hopefully end up with an equal distribution of l and d amino acids.

The decrease in entropy produced when a highly organized system results from less organized matter has often been raised as an obstacle to the evolution of life from non-life. The second law of thermodynamics applies to chemical and physical systems which are isolated in the sense that energy does not cross the boundary of the system. In such systems, entropy tends to increase or the state of the system becomes progressively more random.

A feature of the evolution of living organisms and of many processes taking place within living organisms is that in them entropy appears to decrease at the expense of a greater entropy increase in the environment. This point was clearly made by Schroedinger in his book "What is Life". Living systems are not isolated. Energy does cross the boundaries of the system. This state of affairs is consistent with the second law.

There is no reason to doubt that we shall rediscover, one by one, the physical and chemical conditions which once determined and directed the course of chemical evolution. We may even reproduce the intermediate steps in the laboratory. Looking back upon the biochemical understanding gained during the span of one human generation, we have the right to be quite optimistic. In contrast to unconscious nature which had to spend billions of years for the creation of life, conscious nature has a purpose and knows the outcome. Thus the time needed to solve our problem may not be long. It is unnecessary to belabor the difficulty of the task or the immensity of the prospect for any man's philosophic position. It is superfluous to discuss the sceptical and provincial viewpoint that would shrink from pursuing it, for what is at stake is the chance to gain a new perspective of man's place in nature - an entirely new level of discussion on the meaning and nature of life.

Over 500 years ago, Copernicus in De Revolutionibus Orbium Coelestium reversed the scientific thinking of his time about man's place in the physical universe. A hundred years ago, Darwin's theory of evolution destroyed age-old beliefs of the uniqueness of man by tracing his origin from the brute. Today, we are gradually learning to accept the Oparin-Haldane hypothesis that life is only a special and complicated property of matter and that basically there may be no difference between a living organism and lifeless matter.

Figures

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COMPOSITION OF SUN

HYDROGEN	87.0 %
HELIUM	12.9
OXYGEN	0.025
NITROGEN	0.02
CARBON	0.01
MAGNESIUM	0.003
SILICON	0.002
IRON	0.001
SULPHUR	0.001
OTHERS	0.038

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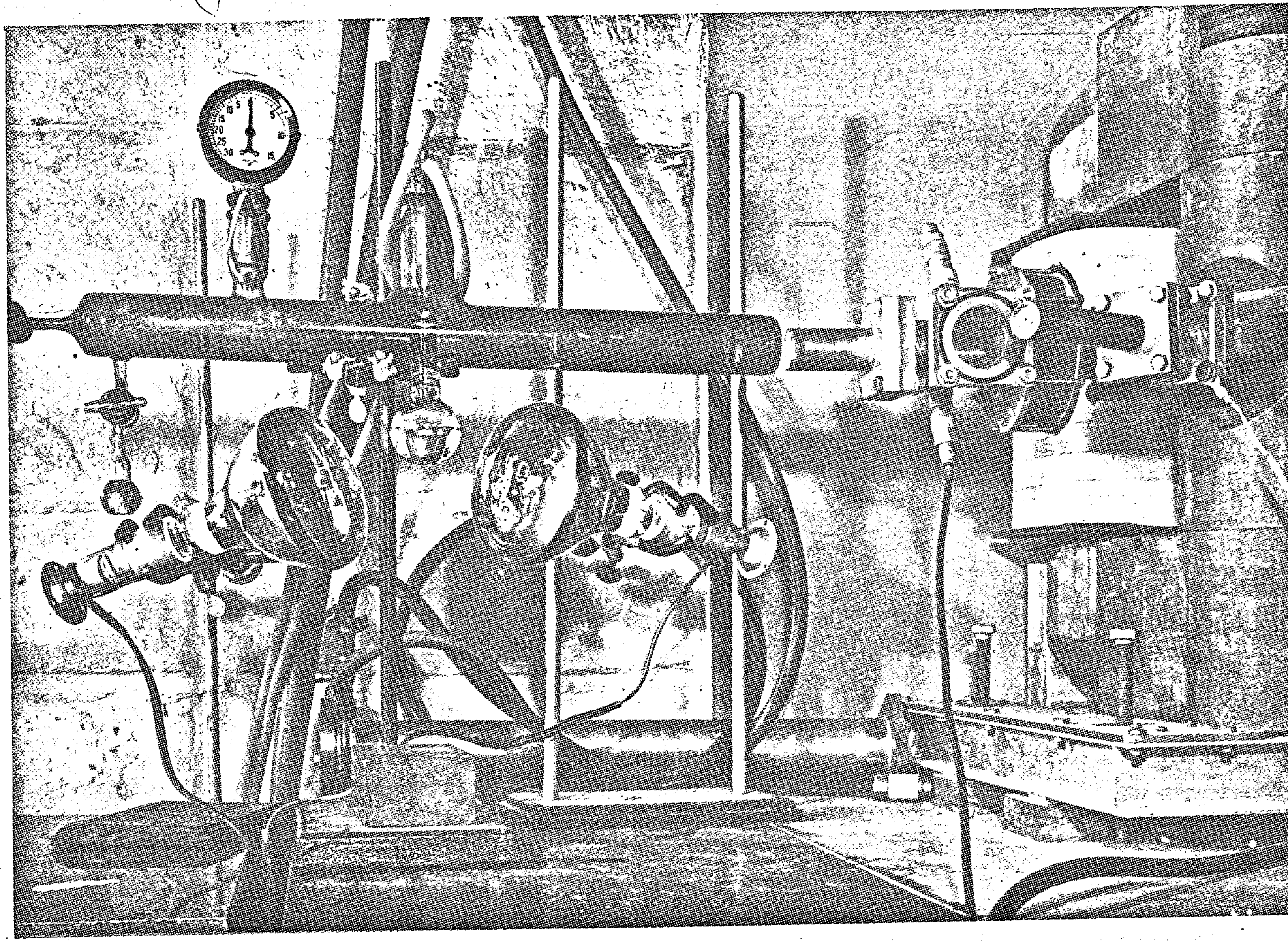

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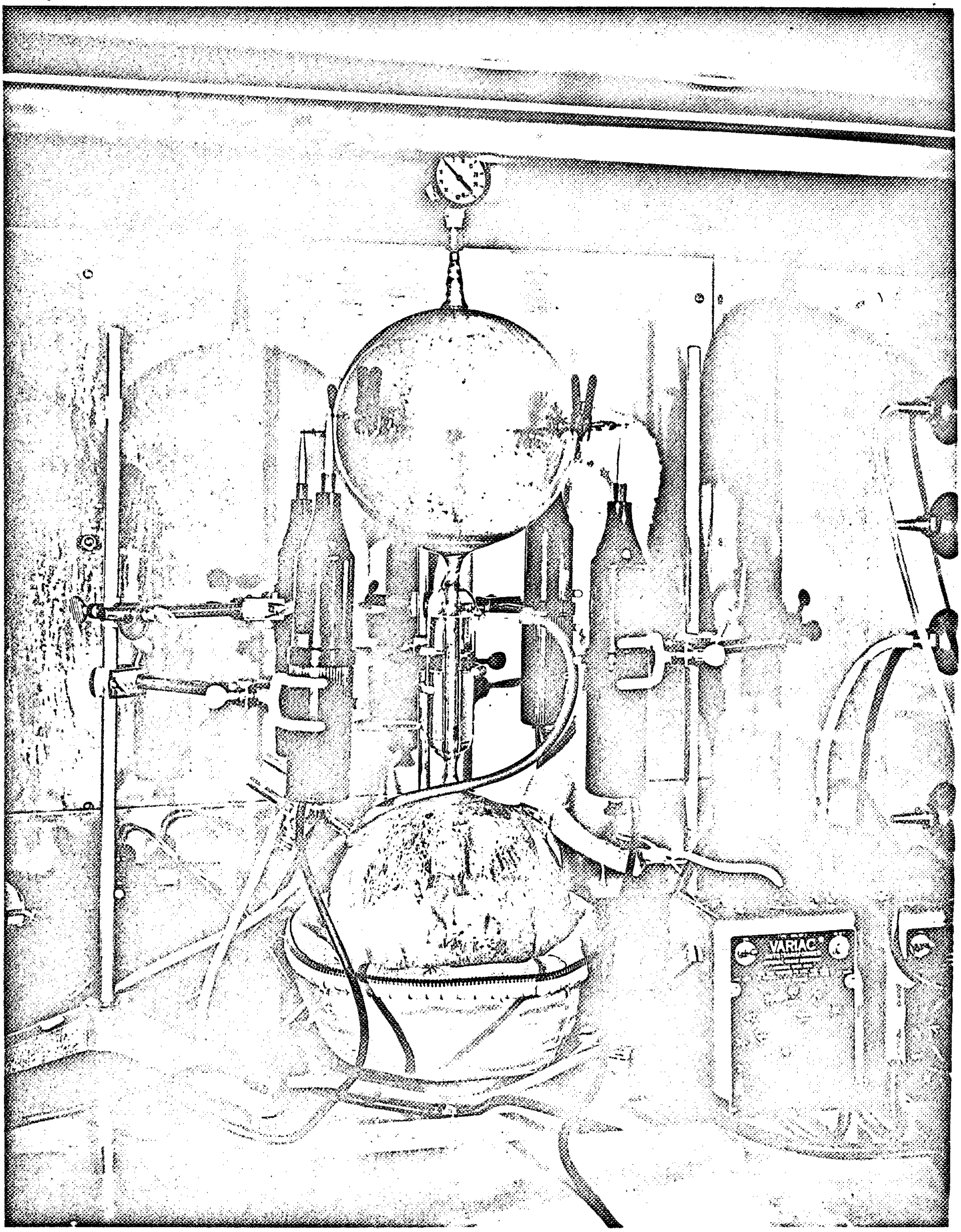

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