Lawrence Berkeley National Laboratory
Recent Work

Title
PREBIOLOGICAL SYNTHESIS

Permalink
https://escholarship.org/uc/item/51d8v2fj

Author
Lemmon, R.M.

Publication Date
1973-06-26

PREBIOLOGICAL SYNTHESIS

R. M. Lemmon

June 26, 1973

DISCLAIMER

Prebiological Synthesis

R. M. LEMMON
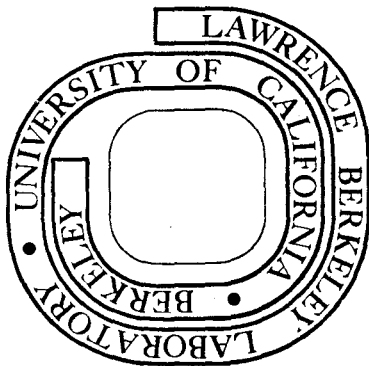
Lawrence Berkeley Laboratory, University of California,

Berkeley, California

SUMMARY: This report reviews the recent progress that has been made toward understanding the necessary-for-life chemistry that took place on the prebiotic Earth, and that led to the appearance of the first living cells. This understanding is based on the simulation, in the laboratory, of conditions analogous to those presumed (on geological and astronomical evidence),to have been present on the primitive Earth. Such research has led to the production of many of the classes of compounds that are key constituents of our contemporary biology. It has also led to the knowledge that abiogenetically produced organic compounds have an intrinsic tendency to assume the forms and the aggregations that are found in living cells. The report concludes with a summary of the exciting new finds of "biological" molecules in interstellar space.

1. Introduction

If one follows Darwinian evolution back through time, living organisms gradually become fewer in numer and simpler in form and function. Finally, back at something more than 3×10^9 years ago, we encounter the first living cell. What were the processes that had to occur on our prebiotic planet in order for that first living cell to be assembled? Just over a century ago the great British physicist John Tyndall referred to the possibilities of studies of these pre-evolutionary processes in the following way (Tyndall 1871):

> "He [Darwin] placed at the root of life a primordial germ, from which he conceived that the amazing richness and variety of life now upon the Earth's surface might be deduced. If this hypothesis were true, it would not be final. The human imagination would infallibly look behind the germ and, however hopeless the attempt, would enquire into the history of its genesis."

In the ensuing century, and particularly in the pas. 25 years, advances in laboratory techniques and instrumentation are such that the attempt now seems far from hopeless. This article will summarize contemporary understanding of the sort of place the prebiological Earth was, and of the processes, namely, the "prebiological syntheses", that led to the first living cells. If John Tyndall were here today, he doubtless would be delighted at the progress in the research that is adding to our understanding of "the history of its genesis".
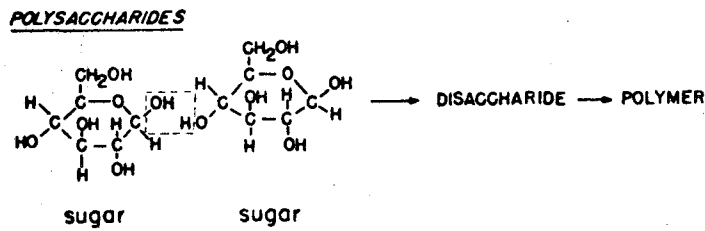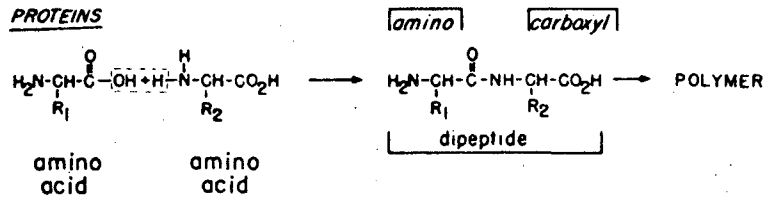
2. The revival of spontaneous generation

In Tyndall's time, men may have thought about what lay "behind the [primordial] germ", but they lacked the scientific techniques to make meaningful investigations. In addition, Louis Pasteur's work in the 1860s seemed to have convinced most people that "life can come only from life", and that to postulate something "behind the germ" (i.e., before the first living cell) was to use the discredited idea of spontaneous generation. However, Pasteur himself knew that his experiments really had not destroyed the theory of spontaneous generation (Dubos 1950). They had simply disproved claims of the appearance of living cells from non-living material in short periods of time (days or weeks) and under simple starting conditions (for example, boiled solutions of sugar and yeast). People with imaginative minds continued to realize that, given complicated enough starting conditions and long enough time, for example, the surface of the prebiotic Earth and millions of years, spontaneous generation was still a logical idea. Indeed, from the standpoint of science, that is, the study of natural phenomena (as opposed to some kind of a supernatural intervention into the Earth's history), it was the only explanation for the origin of life.

In some 6 decades following Pasteur's work it was not logic alone that maintained some lingering, and gradually growing, respectability for spontaneous generation. In this, physics played a key role. A major contribution was the development of atomic spectroscopy, which showed that the observable universe was constructed of the same elements that are found on Earth, and also showed that hydrogen constituted nearly 90% of the universe's atoms. Also, of notable importance, were the discoveries of isotopes and radioactivity, which led to proofs of the Earth's great age. It also

led to far greater accuracies in age determinations than had hitherto been possible from studies in strata deposition and the paleontological record.

By the 1920s, understanding of biological processes had increased to the point that scientific speculations about origins could be undertaken. Because of its emphasis on materialistic philosophy, it is not surprising that the Soviet Union was the locale of the birth of studies on prebiological synthesis, or, as it's often called, "chemical evolution". In 1924, in a booklet entitled "The Origin of Life", the young Russian biochemist A. I. Oparin expressed the idea that life on Earth must have arisen from a preformed "pool"of organic compounds (Oparin 1924). It is remarkable that Professor Oparin has continued his researches in this area right up to the present time; an international meeting will be held next year to honour him and the 50th anniversary of his 1924 publication.

Oparin's ideas were independently reached a few years later by the British biologist J.B.S. Haldane. He suggested that organic compounds must have accumualted on the prebiotic Earth until "the primitive oceans reached the consistency of hot dilute soup" (Haldane 1929, 1933). Finally, after World War II, experimental investigations put the Oparin-Haldane ideas on firm ground and established chemical evolution as an area of scientific research. Spontaneous generation had been revived; it wasn't so "spontaneous", in the sense of fast -- it took perhaps 10^9 years. However, we now have ample reason to believe that, given the intrinsic properties of matter, and given the materials and conditions on the newly

PROTEINS

amino   carboxyl

H_2N-CH-C—OH+H-N-CH-CO_2H ⟶ H_2N-CH-C-NH-CH-CO_2H ⟶ POLYMER

amino acid   amino acid   dipeptide

POLYSACCHARIDES

⟶ DISACCHARIDE ⟶ POLYMER

sugar   sugar

NUCLEIC ACIDS (3 STAGES) RNA SHOWN - DNA LACKS OH ON 2' POSITION

adenine

⟶ POLYMER

adenosine

adenylic acid
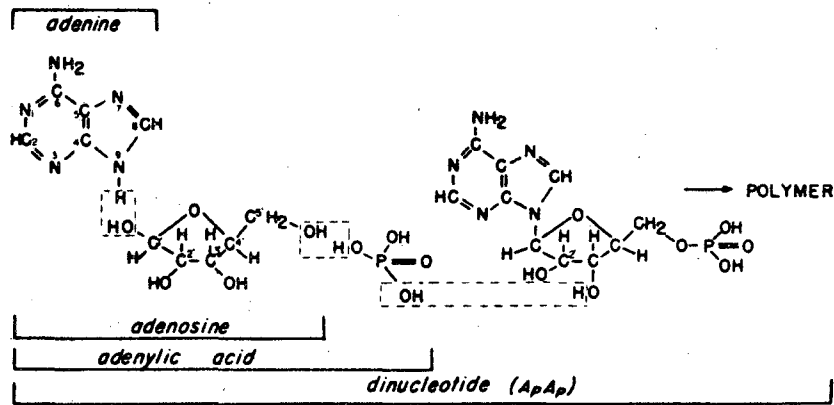
dinucleotide (A_pA_p)

Fig. 2. "Dehydration condensations" leading to the

biopolymers.

Table 1.   Abundance (A) of the most common elements in the solar system[*]

Element	log A	Element	log A
H	12.00	Si	7.50
He	11.21	Mg	7.40
O	8.95	S	7.35
Ne	8.70	Ar	6.88
C	8.60	Fe	6.57
N	8.05		

[*] Aller 1961

A planet forming in such a hydrogen-dominated universe would be expected to have an atmosphere, if it had one, that was composed of hydrogen-containing molecules. Water is such a molecule, but N_2, O_2, and CO_2 (the other major components of the Earth's present atmosphere) are not. What has happened to all the hydrogen, either as the molecule H_2, or in combination with other atoms (such as CH_4, methane, or NH_3, ammonia), that we would expect to find in the Earth's atmosphere? The answer is that H_2 is the lightest of all molecules and thus diffuses very rapidly. The relatively high temperature of our planet (averaging about 15°C), and its size, which gives it an only-modest gravitational field, makes it easy for hydrogen molecules and atoms to diffuse away. Such molecules as CH_4 or NH_3 are broken into their constituent atoms by ultraviolet light and by cosmic radiation. The liberated hydrogen can then diffuse away, leaving

behind the heavier atoms that cannot as easily escape from the Earth. Water, in the Earth's atmosphere, particularly in the upper atmosphere, is steadily being decomposed by ultraviolet light into oxygen and hydrogen; consequently, we are steadily losing hydrogen into outer space, and the O_2 concentration is slowly and steadily increasing. If we look out to the larger and colder planets (Jupiter and its companions), from which it is much harder for hydrogen to escape, we observe atmospheres that contain lots of CH_4 and NH_3. The Jovian atmosphere is probably similar to that of the very-early Earth's. There are additional reasons for believing that the Earth's early atmosphere had much NH_3, in place of the present N_2, and CH_4 instead of the present CO_2:

a. The meteorites that strike the Earth, particularly the stony ones, have chemical compositions not too different from the Earth's crust. The meteorites appear to have originated within our solar system (in the "asteroid belt"), and astronomers taken them to be "left over" samples of the material out of which the planets condensed. The meteorites certainly reflect an origin in a hydrogen-filled universe. Most of their carbon appears as elementary carbon, carbides, and hydrocarbons -- not as carbonate. The iron is mostly metallic or ferrous, and the phosphorus appears as phosphides (Miller and Urey 1959).

b. There are indications, admittedly fragmentary, that the oldest (2 aeons or more) sediments were laid down under an atmosphere more hydrogen-containing than the present one (Rutten 1962). The oldest sediments show increased ferrous:ferric ratios, as well as a shift of their uranium compounds toward lower oxidation stages -- reflecting their deposition in more hydrogen-filled locales.

c. Molecular oxygen is something of a poison to contempoary cells --
a fact difficult to account for if the first living cells had appeared in
an oxygenated environment. Chromosomes appear to operate in an anaerobic
medium, and cell division takes place during a temporary period of anaerobio-
sis (Stern 1955). A possible explanation for this oxygen sensitivity
is that the first living cells appeared under a hydrogenated atmosphere,
and gradually evolved mechanisms to protect themselves against molecular
oxygen as it appeared in the atmosphere.

d. Finally, there is the very success of the experiments discussed
in this article: the formation of biologically relevant compounds on the
irradiation of various gases. When mixtures of methane, ammonia (or N_2),
and water -- the principal constituents of the Earth's presumed early
atmosphere -- are subjected to ultraviolet or ionizing radiation, many
biologically important compounds (amino acids, sugars, purines, nucleic
acid constituents, etc.) are formed. However, similar irradiations of
samples of the Earth's present atmosphere yield little of biological rele-
vance. "As soon as the net [laboratory] conditions become oxidizing,
the organic synthesis effectively turns off" (Shklovskii and Sagan 1966,
p. 231). It appears that the accumulation, on the primitive Earth, of
the necessary "building blocks" for the first living cell required a
hydrogenated atmosphere.

The change from an early, "hydrogenated" atmosphere to the Earth's
present "oxidized" one was enormously speeded by the appearance of green-
plant photosynthesis. As is well known, one of the major reactions of
photosynthesizing plants is to split water into oxygen and hydrogen; the
former is released into the atmosphere as O_2, the latter is combined into
the many plant constituents (amino acids, sugars, etc.). Along with the

change to an oxygenated atmosphere, the Earth developed its present "shield" of ozone (O_3). Without this shield, which protects our planet's surface from the 2100-2900 Å ultraviolet light from the Sun, it is difficult to see how the Earth could have become an abode for life. The importance of the ozone shield was given considerable notice recently because of speculation that the operation of supersonic aircraft might seriously reduce the concentration of ozone in the upper atmosphere (Johnston 1971).

The formation of the Earth's early atmosphere is a complex subject. For example, outgassing of the planet's interior doubtless played a major role in the ultimate composition. However, we can be sure that the processes leading to the appearance of terrestrial life took place under a more highly "hydrogenated" atmosphere than the one we have today. We can also be sure that the chemical environment of the Earth's surface would have been controlled by the nature of its atmosphere. It was these understandings that led to laboratory demonstrations of the probable "prebiological syntheses" that took place on the primitive Earth.

4.2 The effective energies

Almost all the energy reaching the Earth, both now and in pre-biotic times, comes from the Sun. Over 99% of that energy is in the form of visible light and infrared radiation. The visible light is not appreciably absorbed by the gases of the presumed primordial atmosphere; another way of putting this is that the quanta do not individually possess sufficient energy to promote electronic excitation, and subsequent chemical reactions, in these molecules. (Later on in the Earth's history, when sufficiently complicated, visible-light-absorbing pigments were formed, this light could be converted to chemical energy.) The solar infrared

radiation is not intense enough to give the atmospheric gases sufficient kinetic and vibrational energy (heat) to induce chemical reactions through that route. In contrast to the reactions easily induced in simulated pre-biotic-Earth atmospheres (CH_4-NH_3-H_2O mixtures) by ionizing radiation, no appreciable reactions are induced by heat alone until temperatures of about 1000°C are reached. This is a temperature far higher than would have been found, in general, on the Earth's surface once the solid mantle and crust had been formed. It is, however, a temperature which, then as now, is available where there are volcanoes.

The old notion that the primordial Earth was a very hot place (even after the crust was formed) has been steadily losing favor. The Sun is a "main sequence" star, and its luminosity has been slowly increasing over the past 4-5 aeons. It is possible, perhaps even likely, that the Earth's average surface temperature was no higher 4 aeons ago than it is today.

In Table 2 are listed the principal energy sources available at the Earth's surface (Mille and Urey 1959; Calvin 1969, p. 144). These values are for the present time. However, they would have been quite similar on the prebiotic Earth, except for the radioactivity, which would have been greater by a factor of about 4.

Most of these sources of energy have been employed in laboratory experiments directed toward increasing our understanding of the accumu-lation of necessary-for-life compounds on the prebiotic Earth.

Table 2. Main present sources of energy at Earth's surface

Source	Energy average over Earth's surface (10^{19} cal/year)
Total radiation from Sun	133,000
Ultraviolet light	
2500 Å	300
2000 Å	45
1500 Å	0.8
Lightning	2
Radioactivity	0.4
Volcanism	0.6
Meteorite impact	0.5
Cosmic rays	0.0008

Most of these sources of energy have been employed in laboratory experiments directed toward increasing our understanding of the accumulation of necessary-for-life compounds on the prebiotic Earth.

4.3 Favourable sites for prebiological syntheses

The high-energy processes that seem so necessary for the formation of organic compounds are also destructive agents. Organic compounds, once formed, would be rapidly destroyed by the absorption of ultraviolet light or of ionizing radiation. Consequently, interactions between the prebiotic atmosphere and ocean would have been necessary. It is easy to imagine that organic compounds, once formed in the atmosphere, would have been adsorbed onto dust particles blown there by windstorms. The dust (mineral) particles would tend to settle back onto the Earth's surface. It seems that, for further progress in chemical evolution, it would be best for the particles to settle onto the surfaces

of lakes or shallow seas, and then drift to the bottoms. Here, under some meters, or tens of meters, of water, the organic compounds would be protected from destruction by the Sun's intense ultraviolet light. They would also be protected from lightning, from volcanic heat, and, to a lesser extent, from cosmic radiation.

Since ammonia is very water soluble, there is reason to believe that the ocean-atmosphere interface might have been the best of all places for these chemical evolutionary reactions to take place. At that surface there would have been a maximum interaction between CH_4, H_2O, and NH_3 molecules. In addition, the higher-molecular-weight products (such as amino acids) would have been most rapidly sequestered under a water layer that would have minimized subsequent destruction by ultraviolet light or radioactivity.

There are additional reasons for thinking that seas and lakes were important in setting the scene for the appearance of life. For over a century the early oceans have been regarded as the probable birthplace of life on our planet. Studies in paleontology and Darwinian evolution point to this, and chemical evolution seems to point o it too. As was mentioned earlier, J.B.S. Haldane emphasized the role of the primitive oceans and thought that the prebiotic syntheses would have accumulated in them a considerable concentration of organic compounds. It has been calculated on the basis of (a) average quantum yields for the ultraviolet light conversion of hydrogenated-atmosphere gas mixtures to higher molecular weight compounds and (b) assumed values of the ultraviolet photon flux in primitive times, that the prebiogenic Earth's oceans could have developed "a one percent solution of organic matter" in 3×10^8 years (Shklovskii and Sagan 1966, p. 233). For this reason, most chemical evolution experiments have been done in dilute aqueous media.

The ocean would also have been an effective vehicle for the mixing together of different classes of organic compounds formed at separated points on the Earth's surface as a result of, for example, differing temperatures, cosmic ray fluxes, and available mineral surfaces. These surfaces, in addition to their role, mentioned above, of transporting organic compounds from the atmosphere to ocean bottoms, would have played many catalytic roles. Reactions that otherwise take place very slowly are often greatly speeded when the reactants are adsorbed onto favourable sur-faces. The shifting sands on the bottoms of shallow seas appear to be the most likely locale for the appearance of the first living cell.

5. Laboratory investigations of prebiological syntheses

It must be confessed that considerable arguments rage over the ques-tion of what laboratory conditions are, or are not, reasonable simulations of environments on the prebiological Earth. Since our knowledge of that Earth is so sketchy, these disagreements are not surprising. However, most laboratory work on prebiological synthesis has been done in dilute aqueous solutions at room temperature -- simulating the prebiological oceans. The main exception has been the work of Professor S. W. Fox and co-workers at the University of Miami in Florida. They have emphasised the possible role of local high temperatures such as those found in present geothermal areas where there are geysers and/or volcanoes. Using tempera-tures ranging from 150-1000°C the Fox group has contributed intriguing demonstrations of processes that may have played central roles in the appearance of life. This work will be discussed below.

5.1 The biochemical unity of life

As every educated person knows, there is a remarkable unity in the chemistry of life. The carriers of genetic information, the nucleic acids, are constructed of the same units (nucleotides) in all living cells. This is also true of the proteins, whose subunits are the amino acids. Throughout all life the subunits of these two supremely important bio-polymers are the same; the only difference between one living system and another is the frequency and the order in which the subunits appear in a given biopolymer. Destroy that order, and the biochemist can no longer tell whether the subunits came from man or mosquito. All the constituents of sugars and fats, all the energy storing and releasing molecules and mechanisms, all the complex chemistries of metabolism are remarkably similar throughout all life. These similarities point to a common origin for all living species; they also emphasise the successes of recent research in prebiological synthesis. Essentially all the subunits,"or biomonomers", or "building blocks" of life have been formed in the laboratory under simulated primitive-Earth conditions.

5.2 The amino acids

The study of prebiological syntheses received great impetus 20 years ago in the well known experiment of Harold Urey and Stanley Miller (Miller 1953; Miller and Urey 1959). They took a "primitive atmosphere" mixture of methane, ammonia, water, and hydrogen (CH_4, NH_3, H_2O, H_2) and subjected it to electric discharges, thus imitating the effects of lightning storms. The result was the formation of at least four of the amino acids that occur in all proteins. It is known that the passage of electric sparks through such a mixture will cause the formation of a great variety of excited molecules and molecular fragments

such as ions, radicals, and atoms. What the Miller-Urey experiment demon-
strated was that, out of the thousands of ways these fragments could combine
to form new stable products, there was a high tendency to form precisely
the amino acids that are the constituent units of proteins. Other workers
have extended this observation. Of the 20 common amino acids that occur
in proteins, 18 have been found as products of this kind of prebiological-
synthesis experiment. It is now clear that the amino acids common to all
life would have accumulated in great quantity on the prebiological Earth.

5.3 Nucleic acid constituents

In one sense the nucleic acids are more complex than the pro-
teins. Their constituent units (the nucleotides) consist, in turn, of
three parts: a nitrogen-containing base, a sugar, and a phosphate
group. In another sense they are simpler: only five kinds of bases (with
but rare exceptions) are found in the nucleic acids, only two kinds of
sugars, and the phosphate groups are always the same.

The five bases are all but minor variations (additions of NH_2, OH,
and CH_3 groups to two C-H-N compounds known to the organic chemist as
purine and pyrimidine. The structures of these compounds are written as
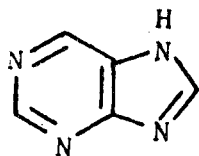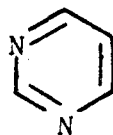
purine   pyrimidine

The five bases are closely related to each other chemically. Their names and atomic compositions (empirical formulae) are:

Adenine, $C_4H_5N_5$

Cytosine, $C_4H_5N_3O$

Guanine, $C_5H_5N_5O$

Thymine, $C_5H_6N_2O_2$

Uracil, $C_4H_4N_2O_2$

Four of these bases have been found as products of prebiological syntheses (thymine is still an exception). Like the 18 amino acids mentioned above, adenine has been found as a result of treating a methane-ammonia-water mixture with ionizing energy. The other bases have been found in the following general way: one takes an aqueous solution of organic (that is, carbon-containing) molecules that have also been found to result from methane-ammonia-water irradiations, and treats the solution further with such "primitive-Earth agents" as heat or ultraviolet light. Thus, cytosine is formed by the simple heating (100°C) of a water solution of urea and cyanoacetylene (the latter reactant is particularly interesting because it has been found in interstellar space -- see below). The other bases have been formed in a similar way and one may confidently expect the early appearance of thymine as a product of such experiments.

The two nucleic-acid sugars, ribose ($C_5H_{10}O_5$) and deoxyribose ($C_5H_{10}O_4$), have been found to result from exposing aqueous solutions of formaldehyde (H_2CO) to ultraviolet light. Formaldehyde is produced on irradiations of primitive-Earth atmospheres and is also known to exist in interstellar space.

The phosphate groups of the nucleic acids are simply phosphoric acid molecules (H_3PO_4) to which the sugar molecules are co-valently bonded. In any watery environment the predominant chemical form of phosphorus is phosphoric acid. Consequently, although there are some problems with respect to the insolubility of the alkaline-earth (e.g., Ca^{++}, Mg^{++}) phosphates, it seems reasonable to envision available phosphate on the prebiological Earth for the formation of the nucleic acid constituents.

5.4 Other important biomonomers

It is not too much to claim that laboratory experiments on prebiological synthesis have resulted in the preparation, under pre-biological-Earth conditions, of representatives of essentially all the important metabolites. One such example are the porphyrins, complex organic molecules that are found as important parts of such biological compounds as haemoglobin, chlorophyll, and vitamin B_{12}. In spite of the complexity of the porphyrins, which have a complicated ring structure and an approximate atomic composition of $C_{20}H_{14}N_4$, such compounds have been found as products of CH_4-NH_3-H_2O irradiations (Hodgson and Ponnamperuma 1968). Another very important class of biocompounds are the sugars. We have already recounted that the nucleic-acid sugars, ribose and deoxyribose, are formed on the simple ultraviolet irradiation of aqueous formaldehyde solutions. It happens that formaldehyde (formed on CH_4-NH_3-H_2O irradiations) is a kind of monomer for sugars. Over a century ago a Russian chemist (A. Butlerov 1861) showed that dilute aqueous alkali (the typical environment of a saline lake) causes formaldehyde to condense to a complex mixture of sugars.

There is no question but that the fats, which are esters, or alcohol derivatives of, fatty acids, would have formed on the prebiological Earth. Experiments unrelated to prebiological synthesis have demonstrated the formation of a wide variety of hydrocarbons, with molecular weights in the hundreds, on the passage of ionizing radiation through methane. (Some geologists have speculated that a significant fraction of the Earth's petroleum deposits may have been formed in this way.) It has also been shown that ionizing radiation causes the direct addition of carbon dioxide to a hydrocarbon, forming the corresponding fatty acid, whose acid properties are given to it by its $-CO_2H$ group. And it should be mentioned here that, even in a predominantly $CH_4-NH_3-H_2O$ atmosphere, some CO_2 would be expected, contributed by the outgassing of the interior. In addition, fatty acids have been shown to be formed on the simple exposure of methane and water to a semi-corona discharge (Allan and Ponnamperuma 1967).

As was recounted above, J.B.S. Haldane asserted in 1929 that the prebiological syntheses would have caused the oceans to reach the consistency of a "dilute soup". The laboratory investigations of the
past two decades have given strong support/that assertion.
to

5.5 Syntheses of the biopolymers

How did the biomonomers (for example, the amino acids) become attached to each other to form the biopolymers (in this case, the proteins)? In all cases the bonding of the monomers is accompanied by the removal of the elements of water -- a H atom from one amino acid, an OH group from the other. The chemist calls this reaction a "dehydration condensation" . These attachments are shown in fig. 2 for three

major classes of biopolymers: proteins, polysaccharides (sugar polymers such as starch and cellulose), and nucleic acids. In each case the elimination of water is indicated by the dotted rectangles.

The removal of the water in the presence of excess water (i.e., in the ocean) is a thermodynamically "uphill" (positive free energy change) reaction. However, the chemical evolutionists have used two methods, both with some success, in trying to demonstrate how this may have occurred on the prebiological Earth. The first is to avoid the oceans, at least until after the polymerization has taken place, and to evoke the notion of reactions taking place in the residues of dried up pools in geothermal areas. The second is to search for simple primitive-Earth compounds whose free energy, and selectivity in promoting dehydration reactions, is such that they can promote dehydration condensations even in dilute water solutions. We shall examine these two methods in turn, and present the highlights of their contributions toward prebiological syntheses.

S. F. Fox and his co-workers at the University of Miami have imagined a prebiological-Earth "scenario" something like the following: (1) amino acids accumulate in the primitive oceans, (2) in a geothermal area, waves splash up on a beach at high tide, forming a pool, (3) because of the local heat, the pool rapidly evaporates, leaving a residue of dry amino acids, (4) the geothermal heat (at approx. 150-200°C) causes polymerization of the amino acids to protein-like material, which the Fox group calls "proteinoids", (5) a returning high tide redissolves the proteinoids, and (6) the redissolved material in the ocean water is now available for adsorption on clay surfaces and also for reprecipitation as cell-like "microspheres" (Fox et al. 1970).

All of the above processes have been demonstrated in the laboratory. The microspheres are obtained on dissolving the proteinoid in warm water, then cooling the water back to room temperature. These microspheres have some intriguing properties in common with modern, living cells: (1) they are about the same size (2 microns in diameter), (2) they have pronounced outer membranes, (3) they exhibit a primitive "reproductive"system: buds break off, absorb molecules from the medium, and become new microspheres, and (4) they can be sectioned and stained. Fox's work led him to suggest that on the primitive Earth there was a "spontaneous synthesis of protein-like material sufficiently similar to yield a protocell" and that "one might thus visualize a natural evolution to cells and subsequently to cellular synthesis of macromolecules" (Fox 1965). At this point the reader should be reminded that the living cell is an enormously complicated aggregation, in comparison to which microspheres are enormously simple. However, the formation of the latter seems to illustrate an intrinsic tendency of matter to aggregate into the forms and structures necessary for the appearance of life.

At has also been found that certain compounds related to hydrocyanic acid (HCN) will cause the formation of small-molecular-weight proteins ("peptides") in dilute water solution. These compounds, examples of which are cyanamide (H_2N-CN) and dicyanamide (NC-NH-CN) are easily formed from CH_4-NH_3-H_2O irradiations (Schimpl, Lemmon, and Calvin 1964). The energy built into these compounds during their formations, and the selectivity with which they remove the atoms (H and OH) from amino acid molecules, give them the ability to co-valently bind amino acids to each other, even in dilute water solution. It has also been shown that the presence of the clay mineral bentonite increases the dicyanamide-promoted

binding together of amino acids (Kenyon and Steinman 1969). The same
reagents will cause the binding of sugars to phosphate groups (thus induc-
ing the key link in the nucleic acid molecules). They will also cause
the dehydration condensation of a nucleic acid monomer ("nucleotide")
at least as far as the trimer -- although the right catalytic surface
must also be present (Sulston et al. 1969).

Although the HCN-related agents have induced the biopolymer formation
up to only three or four units, whereas natural proteins and nucleic
acid have thousands of the constituent monomers, still, this is a pro-
mising beginning. On the prebiological Earth, developing protein and
nucleic-acids chains may have functioned as catalysts for each other's
development. Furthermore, their development may have been strongly
influenced by their adsorption onto mineral surfaces, adsorptions that
could have served to (1) concentrate the monomers, (2) increase their
reactivities towards condensation reactions, and (3) protect them from
deleterious effects of ultraviolet light. In many laboratories the
search is continuing for more-effective "primitive Earth" conditions
to induce biopolymer formation in dilute water solution.

6.   Biopolymer shapes and aggregations

If it be granted that we can see how the biomonomers and biopoly-
mers were synthesized on the prebiological Earth, one would like to
be able to say something further about the particular forms and group-
ings in which they occur in living systems. If we think of the successive
attaching together of amino acids we see that the end result is a bio-
monomer in the form of a random coil. Its only structure (the primary

structure of the biochemist) would be that of the individual, constituent

amino acids. In contrast, natural proteins including all the tremendously

important biocatalysts, the enzymes, have an ordered three-dimensional

structure, or conformation. The principal manifestation of this structure

is the helical form that the proteins (and the nucleic acids) assume. This

form is referred to as the secondary structure. In addition, there is a

tertiary structure, a regular folding of the chains back upon themselves.

A simplified sketch of these three structures is shown in fig. 3.

The helical, secondary, structure is held together principally by

hydrogen bonds between the monomeric units, and this structure may be

disrupted by a change in external conditions, such as the temperature or

acidity of the biopolymer's solution. It is also of note that polymeri-

zation studies have shown that the rate of lengthening of a polypeptide

(small protein) chain increases as soon as a helical configuration is

reached (Doty and Lundberg 1956). In other words, a helical polypeptide

acts as a catalyst for the reactions that increase its own chain length.

It is also known that we can partially disrupt and reform a hydrogen-

bonded tertiary structure while leaving the secondary structure essen-

tially intact (Calvin 1969, p. 188). These changes can be followed by

changes in various spectra of proteins (ultraviolet absorption, nuclear

magnetic resonance, circular dichroism, and optical rotary dispersion).

The enzymatic proteins must have precise conformations so that

reactive centers may be brought in an exact juxtaposition in which

they may exert their catalytic effect. Indeed, the loss of enzymatic

function has been well correlated with the loss of these precise

spatial arrangements (Timasheff 1970). It is quite sure that our

life would not be possible without the existence of spatial organiza-

tion in proteins.

Since our biological proteins have an inbuilt tendency to regain a configuration from which they have been disturbed, we have reason to believe that an abiogenetically produced, random-coil protein would do the same thing. The appearance on the prebiological Earth of proteins with all the properties, including the conformations, of contemporary proteins, appears likely, if not inevitable.

What has been said above specifically about proteins also seems to apply to the nucleic acids. Their conformations are necessary for replication, that is to say, for the transmission of genetic messages. The nucleic acid change from a random coil to the helical structure may also be followed by the observation of ultraviolet-spectral changes, and it is evident in centrifugation studies (Davidson 1969). The random coil-helix changes are reversible; again we are led to the supposition that, on the prebiotic Earth, any polynucleotides that were formed would tend to assume the conformations that we find essential for contemporary life.

7. Syntheses in interstellar space

Since this article is directed toward a readership of physicists, it may be appropriate to end it with a discussion of some "synthesis" research that is being reported by the astrophysicists, and that has considerable meaning for the problem of the origin of life. During the past five years microwave observations of interstellar dust clouds have revealed the presence of about a dozen organic compounds, all of which are extremely interesting from the standpoint of chemical evolution (Buhl 1971). It is an exciting development that has brought together

in formal scientific gatherings physicists and astronomers, on the one hand, and biochemists and organic chemists, on the other. These are groups that previously had little scientific contact with each other, but the advances in radio-astronomy and in prebiological synthesis have greatly reduced that professional isolation.

Until 1968 it was presumed that molecules in interstellar space were no more complicated than diatomic. Species such as OH and CN had been identified by optical spectroscopy in the 1930s. It was assumed, however, that the harsh environment -- with its vacuum, low temperature, and high ultraviolet fluxes -- precluded the possibility of complex molecules. But the advent of radio telescopes that could detect molecular emissions in the microwave region quickly showed that interstellar space contains a great variety of organic molecules, with up to 7 atoms per molecule (e.g., $H_3C-C \equiv CH$, methylacetylene). These molecules are known to exist in the interstellar dust clouds; the dust particles appear to protect the molecules from destruction by the ultraviolet light. They may also serve as surfaces to concentrate the molecules, and as catalysts to speed chemical interactions. Among the molecules that have been identified by the astronomers, that are assumed to play a part in chemical evolution, and that already been discussed in this report, are ammonia, water, formaldehyde, hydrocyanic acid, hydrogen (H_2), and cyanoacetylene. Although methane has not yet been identified, closely related methyl derivatives (such as methyl alcohol and methyl cyanide) have been reported. It is likely that the list of interstellar compounds will grow rapidly, and it is conceivable that very complex organic molecules will be identified.

The presence of these interstellar molecules shows that there is an enormous synthesis of organic compounds taking place in outer space. Possibly, as the Earth condensed it was already supplied with a great variety of necessary-for-life compounds. It is also possible that such compounds had a controlling effect on the subsequent prebiological syntheses that took place. The continuing search for organic molecules in interstellar space will be one of great interest to both the astrophysicists and biologists.

8. Concluding remarks

Recent studies in prebiological synthesis ("chemical evolution") support the scientific theory that we, and all life, exist because of the intrinsic properties of matter. Given these properties, and given the environment of the prebiological Earth, one could expect a gradual accumulation of the necessary-for-life biomonomers and biopolymers. One could also expect a gradual organization of the biopolymers into structures resembling contemporary living cells. W en these structures reached a sufficient level of organization they exhibited the new pro- perties that we identify as manifestations of life. It is the task of the "chemical evolutionist" to uncover more of the details of these prebiological evolutionary processes.

References

ALLEN, W. V., and PONNAMPERUMA, C., 1967, Curr. Mod. Biol., $\underline{1}$, 24.

ALLER, L. H., 1961, The Abundance of the Elements (New York: Wiley-Interscience), p. 192.

BARGHOORN, E. S., 1971, Sci. Amer., $\underline{224}$, No. 5, 30.

BARGHOORN, E. S., and SCHOPF, J. W., 1966, Science $\underline{152}$, 738.

BUHL, D., 1971, Nature $\underline{234}$, 332.

BUTLEROV, A., 1861, Justus Liebig's Ann. Chem. $\underline{120}$, 296.

CALVIN, M., 1969, Chemical Evolution (London: Oxford Univ. Press), pp. 114, 188.

DAVIDSON, J. N. 1969, In The Biochemistry of the Nucleic Acids, pp. 48, 72 (London: Methuen).

DOTY, P., and LUNDBERG, R. D., 1956, J. Amer. Chem. Soc., $\underline{78}$, 4810.

DUBOS, R., 1950, Louis Pasteur: Free Lance of Science (Boston: Little, Brown). p. 187.

FOX, S. W., 1965, In The Origins of Prebiological Systems, edited by S. W. Fox, p. 361 (New York: Academic).

FOX, S. W., HARADA, K., KRAMPITZ, G., and MUELLER, G., 1970, Chem. & Engr. News, $\underline{48}$, June 22nd, 80.

HALDANE, J. B. S., 1933, Science and Human Life (New York: Harper), p. 149.

HALDANE, J. B. S., 1929, "The Origin of Life", in Rationalist Annual (London)

HODGSON, G. W., and PONNAMPERUMA, C., 1968, Proc. Nat. Acad. Sci. USA, $\underline{59}$, 22.

JOHNSTON, H. S., 1971, Science, $\underline{173}$, 517.

KENYON, D. H., and STEINMAN, G., 1969. In Biochemical Predestination, p. 214 (New York: McGraw-Hill).

References, continued

MILLER, S. L., 1953, Science, 117, 528.

MILLER, S. L., and UREY, H. C., 1959, Science, 130, 245.

OPARIN, A. I., 1924, Proiskhozhdenie Zhizni (Moscow: Izd. Moskovskii

    Rabochii).

RUTTEN, M. G., 1962, The Geological Aspects of the Origin of Life on Earth,

    (Amsterdam: Elsevier), p. 106.

SCHIMPL, A., LEMMON, R. M., and CALVIN, M., 1964, Science, 147, 149.

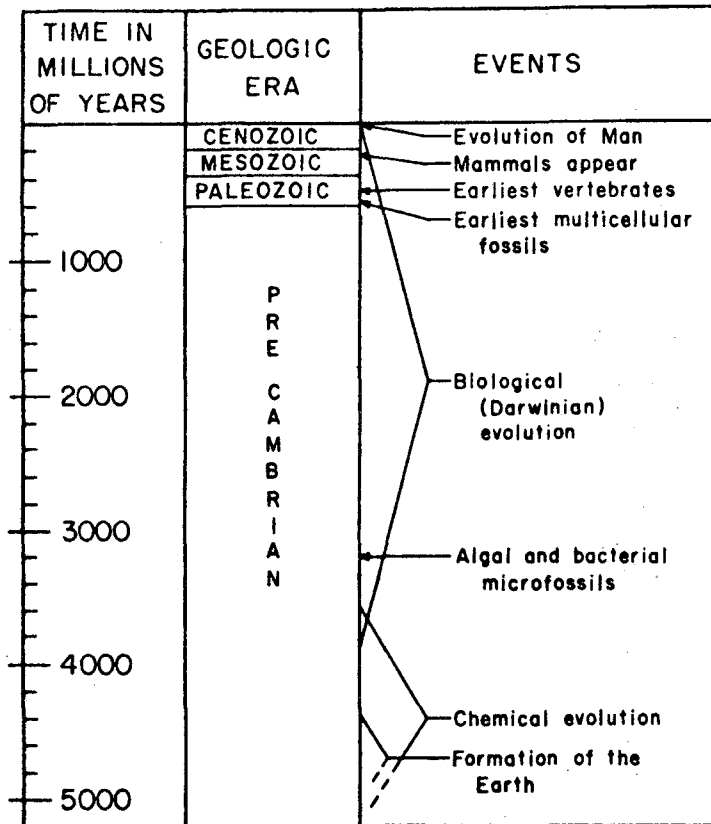SHKLOVSKII, I. S., and SAGAN, C., 1966. Intelligent Life in the Universe

    (San Francisco: Holden-Day), pp. 151, 233.

STERN, H., 1955, Science, 121, 144.

SULSTON, J., LOHRMANN, R., ORGEL, L. E., SCHNEIDER-BERNLOEHR, H.,

    WEIMANN, B. J., and MILES, H. T., 1969, J. Mol. Biol. 40, 227.

TIMASHEFF, S. N., 1970. In The Enzymes, edited by P. Boyer, 3rd ed., Vol. 2,

    p. 392 (New York: Academic).

TYNDALL, J., 1871. Fragments of Science for Unscientific People (New York:
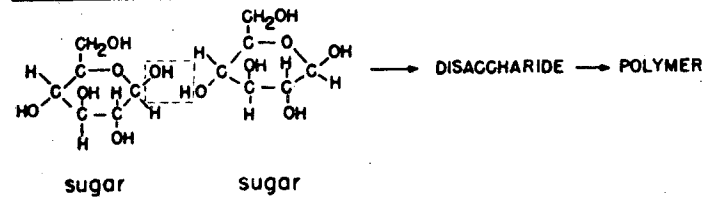
    Appleton), p. 155.

TIME IN MILLIONS OF YEARS	GEOLOGIC ERA	EVENTS
	CENOZOIC	Evolution of Man
	MESOZOIC	Mammals appear
	PALEOZOIC	Earliest vertebrates
		Earliest multicellular fossils
1000	P R E C A M B R I A N	
2000		Biological (Darwinian) evolution
3000		Algal and bacterial microfossils
4000		
		Chemical evolution
5000		Formation of the Earth

XBL715-5177

Fig. 1. Time scale for chemical evolution.
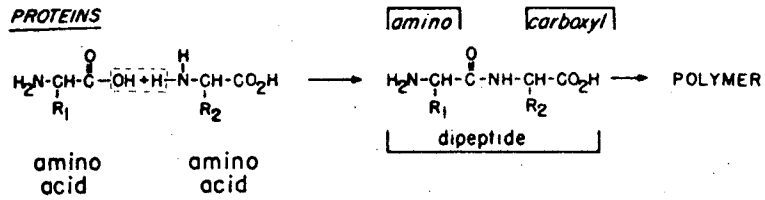
Fig. 2. "Dehydration condensations" leading to the bippolymers.

RANDOM COIL   SECONDARY   TERTIARY STRUCTURE
(primary structure   STRUCTURE   (idealized)
     only)
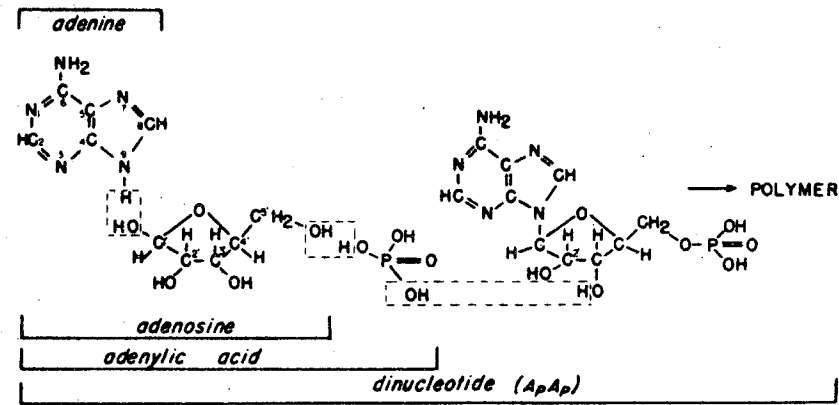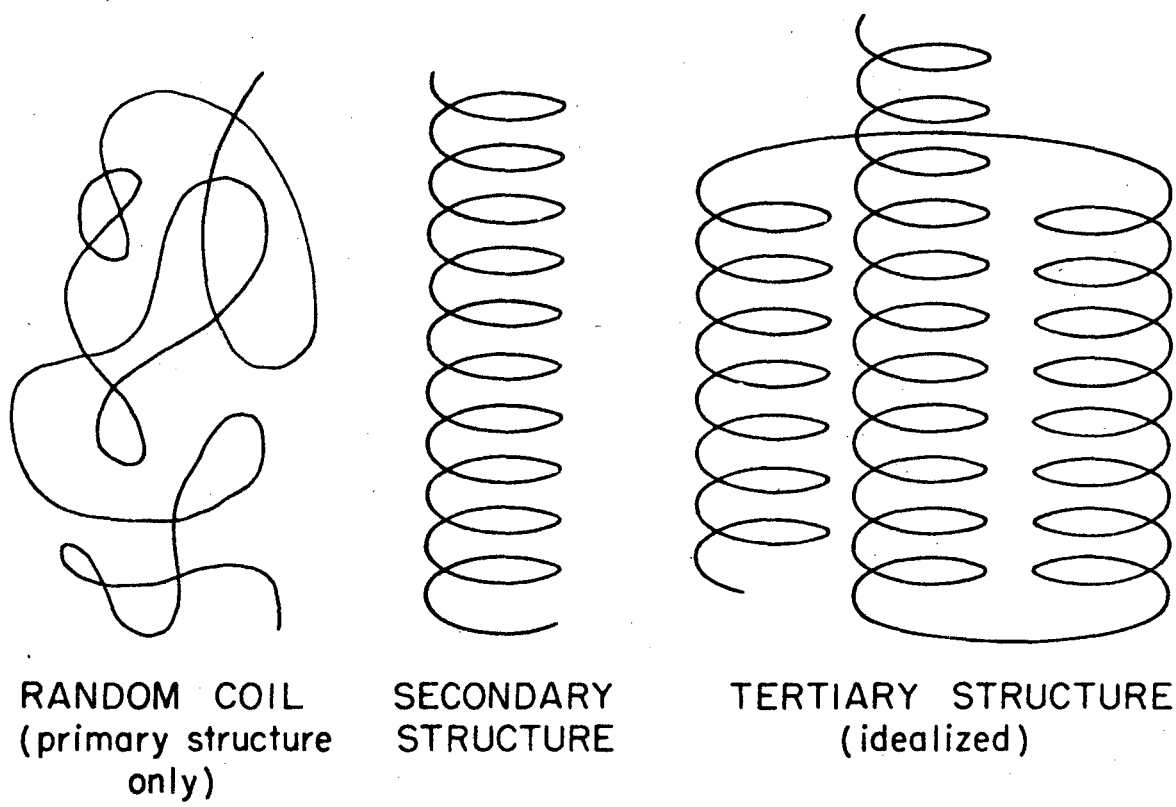
XBL716-5202

Fig. 3.   Primary, secondary, and tertiary structure

of biopolymers.