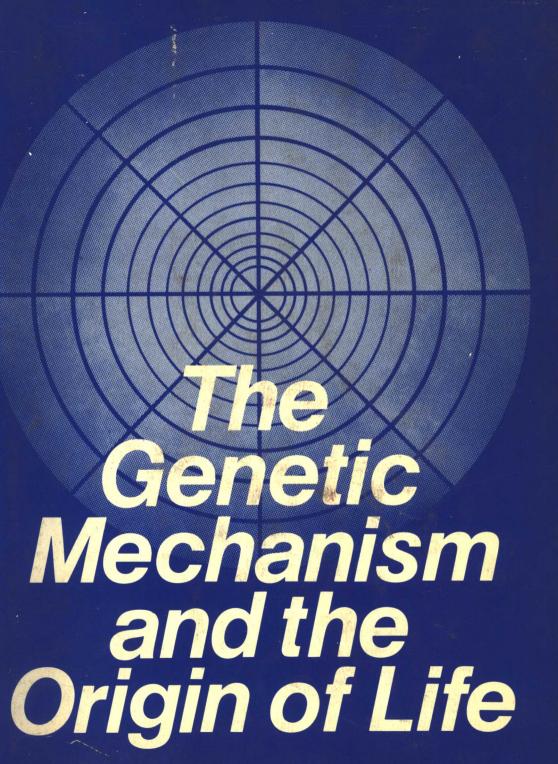
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The Genetic Mechanism and the Origin of Life

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Preface

As shown in the text, there can be little doubt that the genetic mechanism is, for all practical purposes, equivalent to life itself. Consequently, it is unrealistic to seek knowledge of the origin of life and its subsequent evolution without simultaneously searching for an understanding of how this apparatus arose and evolved. Fortunately, the annual publication over the recent years of thousands of papers dealing with the genetic processes has brought the state of knowledge to a level where a synthesis of their major details in relation to life's history is feasible. Because of the voluminous body of literature, no single book can possibly treat all the ramifications of this fundamental subject; subdivision into multiple volumes is necessary. This volume, the first of a trilogy, explores the molecular aspects of the problem in connection with the precellular aspects up to the point of the origin of the cell. The second, currently in progress, is concerned with the subsequent evolution of the cell as revealed by the energyrelated organelles and their genetic apparatuses and by ultrastructural details of other cellular parts. The third volume, as presently planned, deals with developmental, immunological, and other complexities at the organismic level and, in so doing, throws additional light on basic properties of the genetic processes themselves. Thus, the genetic apparatus provides the warp, and evolution the woof, of the intricate fabric that emerges.

Because this present volume is the first attempt at analyzing the genetic mechanism in context with the origin of life, it should be anticipated that several novel ideas might come forth that necessarily are at variance with prevailing dogma. At first one proposal may prove particularly disturbing, the disclosure that one of the two supposedly general principles of biology, the cell theory, is not truly universally applicable to living creatures. When given deeper consideration, however, it becomes apparent that the cell theory implies that life arose directly in the form of a cell without any precellular stages—an implication that appears most unlikely. Especially in light of the extreme com-

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plexity of the genetic mechanism in even the simplest of existing prokaryotes, the conclusion is inevitable that numerous precellular stages of life had to precede these.

The text's employment of viruses as models of those precellular stages may prove equally controversial for the moment. But on further contemplation, the realization must be reached, that, unsatisfactory in the capacity of protobionts as viruses may be, if they are rejected no actual evidence remains as to how life may have arisen. Without evidence, the problem of life's beginning consequently becomes reduced to one fit only for philosophical speculation and, accordingly, would no longer be suitable for investigation by scientists.

This employment of viruses as ancestral protobionts, based on the evidence presented by the genetic mechanism, necessarily invalidates the current practice of using synthetic colloidal particles in that role. But this should by no means be interpreted as implying that the explorations into life's advent by those methods have been meaningless. To the contrary, quite like the alchemists whose searches for the nonexistent lodestone laid the foundations for modern chemistry, explorations into the origins of life via synthetic coacervates, micelles, and proteinoid microspheres have contributed heavily toward an understanding of primeval life.

Whatever merit this study may possess must largely be attributed to those innumerable persons whose brilliant technological achievements and patient labors in the laboratory have revealed the countless details now known about the genetic mechanism. Although the sources of information employed in preparing the text are acknowledged in the usual fashion, it has been possible thus to cite only about 4000 papers, a small portion indeed of the total number of studies actually referred to during the course of this study. The vast majority of references not provided here, however, are to be found in those cited. To all these persons, named and unnamed, the author extends his deepest gratitude and admiration.

In addition, others have contributed in a more direct fashion by making available electron micrographs, light micrographs, and other matter for use herein, for which acknowledgment is made with the illustration as appropriate. In this connection, particular thanks are extended to Drs. Anna S. Tikhonenko, Academy of Sciences of the USSR, and Michel Wurtz, University of Basel, both of whom generously contributed a number of electron micrographs of viruses. Special acknowledgments are made, too, to Dr. Kenneth B. Marcu, of the Institute for Cancer Research, who very cooperatively furnished unpublished information on certain transfer RNAs, and Dr. H. R. Rappaport, Temple University, who supplied advance copies of his studies on ligand binding. Finally, my wife, as always, has collaborated in researching the literature, interpreting the data, and preparing the manuscript in all its stages.

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Origins of Life's Ingredients

The origins of life—being inextricably entwined with the origins of man—hold a fascination without equal in the legends and philosophies of humankind, and while the problem of life's beginnings has been the focus of attention for at least several millennia, only in the very recent past has enough precise information become available so as to permit discussion at the level of scientific investigation. The nature of the problem, however, places it beyond quick and immediate solution. Consequently, while much has already been written on the subject since the early 1950s, the coming years undoubtedly will witness the appearance in print of a still greater body of literature. This probability arises first through the realization that until reasonable solutions are found to those problems which its origins raise, life's own basic properties must in large measure remain incomprehensible (Keosian, 1968; Oparin, 1971). Among the facets which have been greatly illuminated by researches of the past three decades are those concerned with the nature of the biochemical substances of which living things are constructed. The results of these investigations into the origins of life's basic ingredients, first the molecules and later the polymers, provide the subject matter for the present chapter.

1.1. THE SETTING

In studies of the spontaneous origins of those fundamental biochemicals, a second aspect of the major topic becomes evident—as Wald (1974) has pointed out, any inquiry into the beginnings of life of necessity raises a number of broader questions. Not least among the more pressing of these is the nature of the earth immediately after its formation, for an understanding of the natural synthesis of the essential substances obviously requires a knowledge of the chemistry of the atmosphere and other surface features. To gain the necessary

Table 1.1 Time Scale of Life's Origins

Event	Approximate years ago (10 ⁹ years)
Origin of the universe	19–20
Origin of our galaxy	15-16
Origin of the sun	56
Origin of the earth	4.6
Oldest rocks of earth	3.8
Origin of Life on earth	3.0
Oldest known fossils	2.86

factual background, the corresponding traits of other planets need investigation, and to comprehend those data, the origins of the solar system, the galaxies, and the universe in turn are requisite (Table 1.1). As solid data are available only from the earth and other planets, the present study is restricted to the members of the solar system.

1.1.1. Conditions on Other Planets

The spacecraft sent to explore other planets by the Russians and Americans have provided in a few short years more direct evidence about the members of the solar system than had previously been gained by earthbound investigators over several centuries (Rasool, 1972). As a consequence, it is becoming evident that new efforts need to be made toward reevaluating the nature of the atmosphere of the primitive earth. Moreover, the new information seems to have laid to final rest all hopes that life* would be found on our neighboring planets.

The Terrestrial Planets. Of the four terrestrial planets, Mercury, Venus, Earth, and Mars (Table 1.2), only the first remains scantily explored, but its atmosphere is believed to be thin and its surface temperatures high. The second, Venus, had long resisted telescopic investigations, for its surface features have been veiled from view by a permanent cloak of clouds. Beginning toward the close of 1967, several series of spacecraft were able to establish more clearly the nature of its atmosphere and surface conditions. Venera 4, which arrived at this planet on October 18, was followed in sequence by her sister craft, Venera 5 to Venera 10 (Keldish, 1977); together these have es-

^{*} Here the term *life* is restricted to protein-containing forms, as these are the only actual living things known. Although somewhere in the universe silicon-bearing types or other variants may exist, the present usage appears reasonable and justifiable.

tablished that the Venusian surface temperature is $747^{\circ} \pm 20^{\circ} K$ (474°C), and that the atmosphere has a pressure of 90 ± 15 atm. On 19 October of the same year, Mariner 5 began flying past Venus at a distance of 4100 km and explored the atmosphere by means of radio waves. By these means the atmospheric composition was determined as being 95% CO₂, 4% N, 0.4% O₂, and 0.1% H₂O. According to Rasool (1972), the quantity of water detected would, if fully condensed, be sufficient to provide a covering only 10 cm deep over the surface of the planet.

On Mars, the surface temperature and atmospheric pressure have now been shown to be as unfavorable for life as those on Venus, but in the opposite sense. During 1976 two Viking unmanned spacecraft assumed orbits around the planet, Viking 1 beginning on 20 June and the second on 7 August (Soffen, 1976). Preliminary results (Hess et al., 1976b; Nier and McElroy, 1976; Owen and Biemann, 1976; Owen et al., 1976) indicated an atmosphere less than 1.0% as dense as that on earth, at the surface having a mean pressure of 7.65 millibars and a temperature range of 188°K to 244°K during a summer day (Hess et al., 1976a). As on Venus, this thin atmosphere consisted almost entirely of CO₂. Only small quantities of N₂, Ar, O, O₂, and CO were found in the earliest analyses, while Kr, Xe, and Ne were detected later. Much of the relatively scant H₂O that appears to be present on Mars is captured on the surface in the form of permanent polar ice caps; that at the north pole, at a summer temperature near 205°K, was estimated as ranging from 1 m to 1 km in thickness. This was not in the form of a continuous sheet but was extensively broken, at least in the peripheral region, to expose the underlying surface (Farmer et al., 1976; Kieffer et al., 1976). No evidence was found for the existence of a permanent CO₂ cap, although the development of a temporary one during the winter was not ruled out. In view of the severe cold, the relative lack of water, and the unfavorable composition of the atmosphere, the apparent absence of life thus far reported is scarcely surprising (Levin and Straat, 1976).

The Jovian Planets. In contrast to the four terrestrial planets, which consist largely of iron, nickel, and silicates, the outer or Jovian members of the solar system are made predominantly of hydrogen and helium. Hence their density is more like that of the sun, that of Jupiter being 1.33 g/cm³, and Saturn only 0.71 g/cm³; these values compare to the earth's 5.5 g/cm³ (Table 1.2). As a result of the Pioneer 11 mission, which flew by the planet in December, 1974, much has been learned about Jupiter's atmospheric composition and temperature. Because of the clouds which conceal almost all of the surface, no firm data are presently available below heights of 40 km, however. In the zone beginning with that elevation and extending upward 100 km, the clouds were reported to consist of aqueous and particulate ammonia, ice, and ammonium hydrogen sulfide suspended in an atmosphere whose composition is mostly hydrogen and helium; these elements constituted 65% and 22% of the total, respectively. Above that zone hydrogen and helium also prevailed, apparently in

Table 1.2 The Planets and Their Atmospheres

				Surface tempera-					Atmospl	eric	Atmospheric composition $(st)^{b}$	n (%)	q				Density
Planet	Mean distance ^a	Diameter (km)	(g/cm^3)	acure (°K)	н	He	He CO ₂ NH ₃	NH3	02	N ₂	Н20	Ar	CH4	С2Н6	н2ѕ	Ar CH4 C ₂ H ₆ H ₂ S Other (atm)	(atm)
Terrestrial	-																
Mercury	57.9	4,840	5.2	7007													near 0
Venus	108.2	12,200	5.06	747			95		0.4	4	0.1						100
Earth	149.6	12,756	5.5	290			+		21	78	0.01	н					٦
Mars	227.9	6,760	4.12	188-244			95		0.1-0.4	2–3	0.1-0.4 2-3 0.01-0.1 1-2	12				NO2	0.008
Jovian																	
Jupiter	778.3	142,700 1.33	1.33	125	65	22		55			13		+	+	+		53
Saturn	1,427	120,800	0.71	∿100													
Uranus	2,869	47,600	1.15	ى 55													
Neptune	4,498	44,400	1.54														
Pluto	2,900		0.37-2.0	43	+	+							+			Ne?	
																į	

 $^{\bf a}_{\rm Mean}$ distance from sun in km \times 10^{6} . $^{\bf b}_{\rm Plus}$ marks indicate the presence of minute or undetermined percentages.

the same ratios, but methane, methyl residues, acetylene, and ethane also abounded (Smoluchowski, 1975). The surface temperature at the equator was found to be approximately 160°K (Orton, 1975).

Although little is known of the conditions on Saturn, its atmosphere may be suspected to be largely of hydrogen and helium, plus ammonia and methane. Since water is present in its rings, it may also be presumed to occur to some extent in the atmosphere (Klein, 1972). There is no reason to assume that surface temperatures might be more favorable for life than those of Jupiter. Pluto, too, being the most remote, is the least known member of the solar system. Moreover, its small size, which recently was determined as being smaller than the moon (Cruikshank et al., 1976), also contributes heavily to this relative absence of knowledge. However, the presence of solid methane has been detected on its surface where temperatures of about 43°K may prevail (Hart, 1974); its atmosphere could consist largely of neon.

As none of the other planets in our solar system has an atmospheric constitution and thermal conditions conducive to the formation of life (Margulis et al., 1977), explorations into the beginnings must remain for the present to some extent in the realm of speculation. This new knowledge should nevertheless provide a firmer basis for deducing the probable composition of the earth's earliest atmosphere and its subsequent evolution. Present views are outlined below.

1.1.2. Primitive Terrestrial Conditions

To date, in experiments designed to elucidate possible origins of life's substances, it has been the consistent practice to assume that the atmosphere of the primitive earth had a composition similar to that of the Jovian planets (Urey, 1952, 1960). Thus it has been accepted as having consisted largely of hydrogen and helium, together with smaller amounts of ammonia, water vapor, and methane. Whether or not such an atmosphere prevailed on the earth immediately after its solidification is presently an unresolvable problem. If such an atmosphere did exist at first, however, the evidence from Mars and Venus strongly suggests that it must soon have become enriched with CO₂ and Ar by outgassing from the crust—argon is being released from the moon's crust even today, although there has been no volcanic activity for several billion years. Since helium and argon are inert at ordinary temperatures, they can well be omitted from experimental atmospheres, but if realism is a goal, the presence of reasonable percentages of CO₂ certainly should be requisite in future experiments.

The Primitive Atmosphere. As stated above, the Jovian type of atmosphere has provided the general basis for experimental syntheses under prebiotic conditions (Oparin, 1957, 1968). Although the constituents vary widely from laboratory to laboratory, the artificial models typically contain far larger proportions of H₂O, CH₄, and NH₃ than actually found on Jupiter by space

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probes (Miller and Urey, 1959; Urey, 1960). Hence they resemble the observed composition chiefly in containing H_2 in abundance, so that they are of a reducing rather than an oxidizing nature as the terrestrial atmosphere is today. According to some recent reports, O_2 was probably not completely absent after water had accumulated on the earth's surface to some extent but could have been maintained at a level of about 0.02% of the total composition. This supposition seems even more justifiable in view of the proportions now known to exist in the Venusian atmosphere. It is speculated that the oxygen resulted from the bombardment of the seas by certain wavelengths of ultraviolet light, which dissociate water into its elements. As it accumulated in the atmosphere, however, it would have been converted into O_3 by the same rays. As this ozone absorbs these rays, the physicochemical feedback mechanism would have resulted in an equilibrium between H_2O and O_2 at the atmospheric level cited above (Berkner and Marshall, 1965; Rutten, 1969, 1970).

Ammonia, too, is a necessary ingredient in the atmosphere, but probably never exceeded a partial pressure of 10^{-5} atm, at least after large seas were established. Being very soluble in water, it would have existed largely as NH₄⁺ in the oceans if their alkalinity had been near pH 8, as it is at present (Miller and Urey, 1959). Under those conditions it probably never exceeded a concentration of 0.01 M in the seas, because of the absorption of NH₄⁺ by clay minerals (Sillen, 1967; Bada and Miller, 1968); this concentration in solution would be in equilibrium with an atmospheric partial pressure of 10^{-5} atm of NH₃ (Miller, 1974). With the passing of geologic time, there was a gradual decrease in the amount of hydrogen in the atmosphere, and as hydrogen became scarcer, ammonia probably diminished to even smaller proportions, for it is unstable in the absence of hydrogen.

Methane is usually considered vital to the origin of organic compounds and, in the descriptions of experiments on prebiotic syntheses that follow, is frequently an important ingredient. However, some experimenters have found ethane more effective than methane. Carbon dioxide may have been no less significant in prebiotic syntheses, at least toward the end of the early stages, for reasons that become clearer in subsequent discussions. As suggested above, the atmospheres of the two planets whose orbits bracket that of the earth certainly strongly intimate the presence of ample concentrations of carbon dioxide. Although often omitted in such experiments, hydrogen sulfide must necessarily have formed a reasonable portion of the primitive atmosphere, for it too has an important role to play early in life's history.

Although the reducing atmosphere just discussed is the one most usually postulated to have existed, it is not universally accepted by any means. Some laboratories suggest that an oxidized atmosphere such as that of Mars could have prevailed on the primitive earth (Hubbard et al., 1971, 1973; Tseng and Chang, 1975). Several experiments performed with such oxidized atmospheres as combinations of CO, CO₂, H₂O, and N₂ resulted in the synthesis of bio-

chemicals when exposed to ultraviolet radiation. Consequently, free NH₃ is not an essential ingredient for the formation of these substances. An additional school of thought postulates the earth to have been molten during its period of accretion (Fanole, 1971; Armstrong and Hein, 1973). This point of view has received further support through certain results of the exploration of other planets by space probes, such as the granite found on the surface of Venus, the caldera-type craters discovered on Mars, and the basalt and anorthosite brought back from the moon (Shimizu, 1975). Had the earth been subjected to high temperatures during its formation, when it cooled its atmosphere would have been rich in H₂, CO, and HCN, while the seas would have contained formaldehyde, ammonia, and good concentrations of nitrate, sulfate, and phosphate ions.

The Primeval Seas. In contrast to the early atmosphere's complete dissimilarity from that of today, the primordial seas, although at first small and shallow (Rubey, 1951, 1955; Dillon, 1974), must have approached existing ones in regard to ionic content. To judge from the needs of primitive life, potassium, sodium, magnesium, phosphorus, calcium, iron, and chlorine probably comprised the major ions, along with NH₄ and a minute quantity of O²⁺, as indicated above. A number of minor components, including manganese and zinc, were also present, but none of these appears to enter into widespread processes of fundamental importance.

In brief, then, the stage for the events preliminary to life's origin was set on a sterile earth devoid of large continents, studded with small, shallow seas, subjected to almost continual volcanism, and blanketed by a completely different type of atmosphere. But the earth itself was not then—nor has it been at any subsequent time—merely an inert stage upon which life underwent its origin and evolution. During every phase of life's development, the earth has been not just an active participant, but one of the main factors in the processes. Nowhere is this statement truer than in the earliest phases of life's history about to be described, for the earth served then as the ultimate source of all the interacting ingredients involved in the formative reactions, including much of the essential energy.

1.2. PREBIOTIC SYNTHESES (STAGE I)

It is in the earliest phase of life's origin, in which the fundamental biochemical molecules were synthesized from inorganic matter (Stage I; see Table 1.3), that experimentation has proven most valuable in elucidating feasible mechanisms. In broad terms, the experiments involve exogenous energy sources and various combinations of the gases (sometimes in solution) considered to have been prevalent in the primordial earth's atmosphere. Two major categories of experiments exist, based upon the nature of the product sought. In

Table 1.3 Stages in the Evolution of Life

Stage of	evolution		
Cosmic	Organic ^a	Name	Characteristics
I	_	Atomic or elemental	Evolution of the ele- ments; origin of sun, earth, etc.
II	I	Molecular; prebiotic synthesis	Origin of the basic bio- chemicals of living things
III	II	Prebiotic poly- merization	Formation of peptides, simple proteins, nucleic acids, etc.
IV	III	Precellular or in- teracting systems	Precellular events
V	IV	Eucellular	Origin and evolution of the cell and advanced organisms

and only this set of stages is referred to in the text.

one of these, the synthesis of amino acids is the principal objective; in the second, the formation of the nitrogenous bases of nucleosides. As a consequence of occasional overlap of results, the two types are not always sharply differentiated.

1.2.1. Syntheses of Amino Acids

The 20 amino acids found in proteins constitute the largest portion of the basic "alphabet" of biochemicals essential to life in general. According to Wald (1964), only nine other "letters" occur universally in living things, and of these, seven (five nitrogenous bases and two pentose sugars) enter into the formation of the two nucleic acids, DNA and RNA. Thus it is evident that living matter is characterized by a relatively small number of different molecular types. But through the capability of these few to polymerize into such long chains as proteins and nucleic acids, they are more than sufficient to provide the infinite variety found among living creatures. It was upon the amino acids that the first experiments of recent decades investigating possible pathways of life's origins were centered.

Electric Discharge Experiments. What is often considered the very first attempt to explore the origins of amino acids along modern lines was that of Miller (1953) at the University of Chicago. A closed system containing a

mixture of four of the gases presumed present in the primitive atmosphere (ammonia, methane, hydrogen, and water vapor from boiling water) was subjected to both spark and silent electric discharges for a week. At the end of that time, a number of amino acids and related biochemicals were found to have been synthesized (Table 1.4). Among the former were included glycine, α -alanine, β -alanine, and aspartic and glutamic acids. These results were confirmed later by Pavlovskaya and Pasynskii (1959), although those workers replaced some of the hydrogen with carbon monoxide and employed a somewhat different type of apparatus.

Spark discharge, simulating lightning in the atmosphere, was widely used as an outside energy source by researchers in this field, who employed a great diversity of "primitive atmospheres." Abelson (1956, 1957) increased the complexity of the gas mixture by adding nitrogen, carbon monoxide, and carbon dioxide to Miller's four components, but a similar catalog of products resulted. More importantly, these studies demonstrated that ammonia could not be replaced by nitrogen and that carbon dioxide could not freely substitute for methane. In an attempt to synthesize the two sulfur-containing amino acids (cysteine and methionine), Heyns et al. (1957) added sulfur dioxide to the gas mixture but were unable to obtain the desired results. However, through the use of an entirely different set of reactants, Oró (1963a) succeeded in lengthening the list of amino acids produced by means of electric sparking. He employed various two- and three-carbon hydrocarbons in concentrated ammonium hydroxide and thus succeeded in adding valine, leucine, and isoleucine to the catalog of products synthesized under possible prebiotic conditions. Another amino acid, methionine, was added to this list through use of a mixture of methane, nitrogen, ammonia, water, and either hydrogen sulfide or methyl sulfhydryl (Ring et al., 1972; Van Trump and Miller, 1972; Miller, 1974).

Another recent study replaced the electric sparking with high-frequency discharge (42.5 megacycles) at 1000 V and 200 mA. When mixtures of methane and ammonia were exposed to this energy source, a tetramer of hydrogen cyanide was produced in addition to a number of such common amino acids as glycine, alanine, and aspartic acid (Yuasa and Ishigami, 1975). The tetrameric hydrogen cyanide and related substances are of frequent use in prebiotic experiments and receive further mention later. A recent series of investigations has exposed various primitive-type atmospheres to silent electric discharge at low pressure (20 mm Hg) for several seconds. When mixtures of methane and ammonia or methane and nitrogen were thus treated, various amino compounds were formed, along with hydrogen cyanide, cyanogen, and cyanoacetylene (Toupance et al., 1975). Only atmospheres rich in nitrogen gave rise to cyanogen and cyanoacetylene. In contrast, when methane and hydrogen sulfide were used, carbon disulfide was formed in yields of several percent if the H₂S concentration was high, that is, between 40 and 50%. Because thiols (CH₃SH and C₂H₅SH) resulted only at lower concentrations of H₂S, it was concluded that 10 CHAPTER 1

H₂S had an inhibiting effect on the synthesis of hydrocarbons (Raulin and Toupance, 1975).

Experiments Using Ultraviolet Light. Among the most abundant energy sources on earth is solar ultraviolet light, which today even in the presence of an ozone layer provides nearly 150 times as many calories annually as lightning (Miller and Urey, 1959). If oxygen is presumed to have been absent from the atmosphere very early in earth's history, ozone also would have been wanting; consequently, the relative effectiveness of this type of radiation would then have been greatly enhanced. Accordingly, a number of investigators have utilized this type of energy in spite of the difficulties imposed by the narrow range of wavelengths provided by available artificial sources. Among the earlier attempts at using ultraviolet were those of Groth and his associates (Groth, 1957; Groth and Wyssenhoff, 1957, 1960). When they tried the 1848-Å wavelength provided by a mercury lamp on methane, ammonia, and water vapor, no amino acids were obtained; however, when the same mixture was exposed to the 1470-Å and 1295-Å wavelengths emitted by a xenon source, several were synthesized.

Because the usual gases employed do not readily absorb the longer ultraviolet rays, as demonstrated by the last experiments cited above, a small number of investigations have made use of water, which does absorb them. In one set of experiments, Ellenbogen (1958) bubbled methane through a suspension of ferrous sulfide in a solution of ammonium chloride exposed to a mercury lamp, which resulted in the synthesis of valine, phenylalanine, and methionine. Bahadur (1954; Bahadur et al., 1958) permitted sunlight to act upon paraldehyde solutions, variously contained ferric chloride, ferric nitrate, or ammonia, and succeeded in producing serine, asparagine, and aspartic acid. Irradiating at a wavelength of 1848 Å produced glycine and alanine from formaldehyde, inorganic carbonates, and amonia; similar wavelengths have also been employed on hydrogen cyanide with comparable results (Noda and Ponnamperuma, 1971). Formaldehyde and ammonium salts in aqueous solution, exposed to the rays of a high-pressure mercury lamp, have produced serine, valine, and phenylalanine in addition to several simpler amino acids. Similarly Steinman et al. (1968) made use of a mercury lamp but irradiated ammonium thiocyanate with it. As a result, a sulfur-containing amino acid, methionine, was obtained, as well as a number of the more usual types.

A method for utilizing the longest ultraviolet rays ($\lambda > 2500 \text{ Å}$) with gaseous mixtures employed the introduction of a suitable photon acceptor. Among those gases that have been used for this purpose is hydrogen sulfide, which absorbs a broad continuum of rays extending from wavelengths <2700 Å down to that of the vacuum ultraviolet. For one example, Sagan and Khare (1971) were able to synthesize a number of amino acids from various "primitive atmospheres" containing this substance; among those produced were alanine, glycine, cysteine, serine, and glutamic and aspartic acids. These workers