CHAPTER 26
EARLY EARTH AND THE ORIGIN OF LIFE

OUTLINE

I. Introduction to the History of Life
   A. Life on Earth originated between 3.5 and 4.0 billion years ago
   B. Major episodes in the history of life: *a preview*

II. Prebiotic Chemical Evolution and the Origin of Life
   A. The first cells may have originated by chemical evolution on a young Earth: *an overview*
   B. Abiotic synthesis of organic monomers is a testable hypothesis: *science as a process*
   C. Laboratory simulations of early Earth conditions have produced organic polymers
   D. Protobionts can form by self-assembly
   E. RNA was probably the first genetic material
   F. The origin of hereditary information made Darwinian evolution possible
   G. Debate about the origin of life abounds

III. The Major Lineages of Life
   A. Arranging the diversity of life into the highest taxa is a work in progress

OBJECTIVES

After reading this chapter and attending lecture, the student should be able to:

1. Provide at least two lines of evidence for the antiquity of life.
2. Describe the contributions that A.I. Oparin, J.B.S. Haldane, Stanley Miller and Harold Urey made towards developing a model for abiotic synthesis of organic molecules.
3. Provide plausible evidence to support the hypothesis that chemical evolution resulting in life's origin occurred in four stages:
   a. Abiotic synthesis of organic monomers
   b. Abiotic synthesis of polymers
   c. Formation of protobionts
   d. Origin of genetic information
4. Describe the basis for Whittaker's five-kingdom system.
5. Describe three alternatives to the five-kingdom system and explain the rationale for each.

KEY TERMS

stromatolites	protobionts	ribozyme

LECTURE NOTES

The history of living organisms and the history of Earth are inextricably linked.

Examples:
- Formation and subsequent breakup of Pangaea affected biotic diversity.
- The first photosynthetic organisms released oxygen into the air and altered Earth's atmosphere.
- *Homo sapiens* has changed the land, water and air on a scale and at a rate unprecedented for a single species.

In order to reconstruct life's history, scientists use evidence from:

- The fossil record, which is less complete the older the strata studied. In fact, there is no fossil record for the seminal episode of the origin of Earth's life.
- Contemporary organisms which, in their molecules and anatomy, carry traces of their evolutionary histories.

I. Introduction to the History of Life

A. Life on Earth originated between 3.5 and 4.0 billion years ago

Life probably appeared relatively early in the Earth's history. Scientists have found isotopes of carbon in 3.8 billion year old rocks in Greenland.

Because of the relatively simple structure of prokaryotes, it is reasonable to assume that the earliest organisms were prokaryotes. The fossil record supports this notion.

- Fossils similar to spherical and filamentous prokaryotes have been recovered from stromatolites 3.5 billion years old in western Australia and southern Africa (see Campbell, Figure 26.2).

Stromatolites = Banded domes of sediment similar to the layered mats constructed by colonies of bacteria and cyanobacteria currently living in salty marshes (see Campbell, Figure 26.1)

- The western Australian fossils appear to be of photosynthetic organisms, which indicates life evolved before these organisms lived—perhaps some 4 billion years ago.
- Other fossils similar to the prokaryotes have been recovered from the Fig Tree Chert rock formation in southern Africa which date to 3.4 billion years.

B. Major episodes in the history of life: *a preview*

Campbell, Figure 26.3, is a diagram of some major episodes in the history of life.

Fossil evidence suggests that prokaryotes appeared at least 2 billion years before the oldest eukaryotes

- Two distinct groups of prokaryotes, Bacteria and Archaea, diverged early, between 2 to 3 billion years ago.
- Photosynthetic bacteria started the production of oxygen about 2.5 billion years ago, setting the stage for aerobic life.

Eukaryotes emerged some 2 billion years ago

- Strong evidence supports the hypothesis that eukaryotic cells evolved from a symbiotic community of prokaryotes

Plants, fungi, and animals arose from distinct groups of unicellular eukaryotes during the Precambrian.

- Plants evolved from green algae.

- Fungi and animals arose from different groups of heterotrophic unicells. Based on molecular evidence, fungi are more closely related to animals than they are to plants.

The oldest fossils of animals are those of soft-bodied invertebrates from about 700 million years ago. The basic body plans of most of the modern animal phyla probably arose in the late Precambrian.

The transition from the aquatic environment to land was a pivotal point in the history of life.

- The first terrestrial colonization was by plants and fungi some 475 million years ago; the move may have depended upon a beneficial association between the two groups.
- The transformation of the landscape by plants created new opportunities for all forms of life.

II. Prebiotic Chemical Evolution and the Origins of Life

A. The first cells may have originated by chemical evolution on a young Earth: *an overview*

Life originated between 3.5 and 4.0 billion years ago. During this timespan the Earth's crust began to solidify (4.1 billion) and bacteria advanced enough to build stromatolites (3.5 billion).

The origin of life was possible in Earth's ancient environment, which was different from today:

- There was little atmospheric oxygen.
- Lightning, volcanic activity, meteorite bombardment, and ultraviolet radiation were more intense.

One hypothesis about the first living organisms is that they were the products of a chemical evolution that occurred in four stages:

1. Abiotic synthesis and accumulation of monomers, or small organic molecules, that are the building blocks for more complex molecules
2. Joining of monomers into polymers (e.g., proteins and nucleic acids)
3. Formation of *protobionts*, droplets which formed from aggregates of abiotically produced molecules and which differed chemically from their surroundings
4. Origin of heredity during or before protobiont appearance.

B. Abiotic synthesis of organic monomers is a testable hypothesis: *science as a process*

In the 1920', A.I. Oparin and J.B.S. Haldane independently postulated that the reducing atmosphere and greater UV radiation on primitive Earth favored reactions that built complex organic molecules from simple monomers as building blocks. This is not possible today because:

- Oxygen in Earth's oxidizing environment attacks chemical bonds, removing electrons. An important characteristic of the early atmosphere must have been the rarity of oxygen.
- The modern atmosphere has a layer of ozone that screens UV radiation, so the energy required to abiotically synthesize organic molecules is not available. On primitive Earth, energy was available from frequent lightning and intense UV. radiation that penetrated the atmosphere.

Stanley Miller and Harold Urey tested the Oparin/Haldane hypothesis (see Campbell, Figure 26.4). They simulated conditions on early Earth by constructing an apparatus containing H_2O, H_2, CH_4 and NH_3.

- Their simulated environment produced some amino acids and other organic molecules.
- Now we know the atmosphere of early Earth probably included CO, CO_2, and N_2, and was less reducing than the Miller-Urey model, and thus, less favorable to formation of organic compounds.
- Additional experiments have produced all 20 amino acids, ATP, some sugars, lipids and purine and pyrimidine bases of RNA and DNA.

C. Laboratory simulations of early Earth conditions have produced organic polymers

The forming of complex organic molecules, or polymers, from simpler building-block molecules may have been inevitable on the primitive Earth.

Polymers = Chains of similar building blocks or monomers

Polymers are synthesized by dehydration (condensation) reactions. For example:

$$\square\text{—H} + \text{OH—}\square \longrightarrow \square\text{—}\square + H_2O$$

- H and OH groups are removed from the monomers.
- H_2O is produced as a by-product.

Abiotic polymerization reactions in early-Earth conditions must have occurred:

- Without the help of enzymes
- With dilute solutions of monomers (spontaneous dehydration reactions that produce water would be unlikely in already dilute solutions)

Abiotic polymerization does occur with dilute solutions of monomers under certain laboratory conditions:

- Dilute solutions of organic monomers are dripped onto hot sand, clay, or rock. Water vaporizes and concentrates the monomers on the substrate.
- Sidney Fox (University of Miami) used this method to abiotically produce polypeptides called proteinoids.

Clay may have been an important substrate for abiotic synthesis of polymers since:

- Monomers bind to charged sites in clay, concentrating amino acids and other monomers.
- Metal ions (e.g., iron and zinc) could catalyze dehydration reactions.
- The binding sites on clay could have brought many monomers close together and assisted in forming polymers.
- Pyrite (iron and sulfur) may also have been an important substrate. It has a charged surface and electrons freed during its formation could support bonding between molecules.

D. Protobionts can form by self-assembly

Living cells may have been preceded by protobionts.

Protobionts = Aggregates of abiotically produced molecules able to maintain an internal environment different from their surroundings and exhibiting some life properties such as metabolism and excitability

There is experimental evidence for the spontaneous formation of protobionts:

- When mixed with cool water, proteinoids self-assemble into microspheres (see Campbell, Figure 26.5a) surrounded by a selectively permeable protein membrane. These microspheres:
  - ⇒ Undergo osmotic swelling and shrinking
  - ⇒ Have potential energy in the form of a membrane potential
- Liposomes can form spontaneously when phospholipids form a bilayered membrane similar to those of living cells.

- Coacervates (colloidal drops of polypeptides, nucleic acids, and polysaccharides) self-assemble.

E. RNA was probably the first genetic material

Today's cells transcribe DNA into RNA, which is then translated into proteins. This chain of command must have evolved from a simpler mechanism of heritable control.

- One hypothesis is that before DNA, there existed a primitive mechanism for aligning amino acids along RNA molecules, which were the first genes. Evidence to support this hypothesis includes:
  - ⇒ RNA molecules may have been able to self-replicate. Short polymers of ribonucleotides that can base pair (5 – 10 bases without enzyme, up to 40 bases with zinc added as catalyst) have been produced abiotically in test tubes (see Campbell, Figure 26.6).
  - ⇒ RNA is autocatalytic, as indicated by *ribozymes* (RNA that acts as a catalyst to remove introns, or catalyze synthesis of mRNA, tRNA or rRNA).
- RNA folds uniquely depending on sequence (unlike DNA), thereby providing raw materials for natural selection—different molecular shapes (phenotypes) varying in stability and catalytic properties. Replication errors (mutations) probably created additional variation within families of closely related sequences.
- In addition to molecular competition, molecular cooperation probably evolved as RNA-directed protein synthesis produced short polypeptides that catalyzed RNA replication.
- Once this simple machinery for replication and translation of genetic information became sequestered into membrane-bound protobionts, molecular cooperation could be refined as natural selection acted on the level of the entire protobiont.

F. The origin of hereditary information made Darwinian evolution possible

Perhaps this hypothetical membrane-bound protobiont:

- Incorporated genetic information
- Selectively accumulated monomers from its surroundings
- Used enzymes programmed by genes to make polymers and carry out other chemical reactions
- Grew and split, distributing copies of its genes to offspring

If these cell precursors could also grow, divide, and distribute genes to offspring, the descendant protobionts would vary because of errors in the copying of RNA (mutations).

- The variation among related protobionts would be subject to natural selection.
- Evolution in the Darwinian sense—differential reproductive success—presumably accumulated refinements to primitive metabolism and inheritance, including the appearance of DNA as the hereditary material.
  - ⇒ Initially, RNA could have provided the template to produce DNA.
  - ⇒ Because it is more stable, DNA would have replaced RNA as the store of genetic information.
  - ⇒ RNA's role would change as it became an intermediate in translation.

G. Debate about the origin of life abounds

No one knows how life actually began on Earth. The chemical evolution described and supporting lab simulations indicate key steps that could have occurred.

Several alternatives have been proposed.

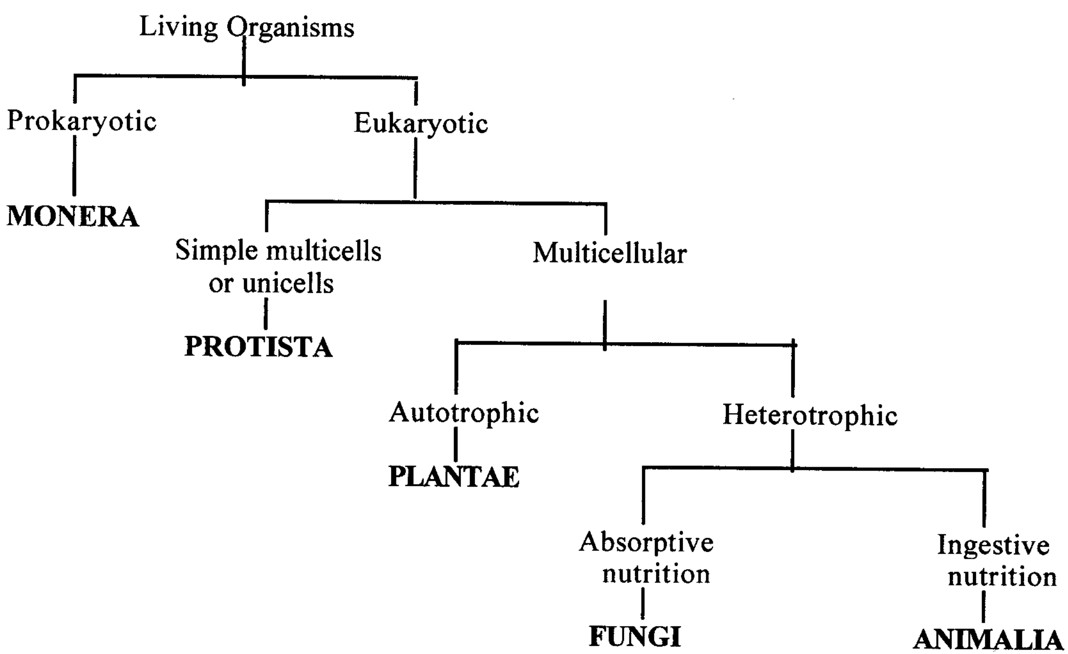
- Panspermia - Some organic compounds may have reached Earth by way of meteorites and comets. Organic compounds (e.g., amino acids) have been recovered from modern meteorites. These extraterrestrial organic compounds may have contributed to the pool of molecules which formed early life.
- Most researchers believe life first appeared in shallow water or moist sediments. Some now feel the first organisms developed on the sea floor due to the harsh conditions on the surface during that time. This position was strengthened in the 1970s by discovery of the deep sea vents. Hot water and minerals emitted from such vents may have provided the energy and chemicals necessary for early protobionts.
- Simpler hereditary systems may have preceded nucleic acid genes. Julius Rebek synthesized a simple organic molecule in 1991. The importance of this molecule was that it served as a template for self-replication (see Campbell, Figure 26.8). This discovery supported the idea held by some biologists that RNA strands are too complicated to be the first self-replicating molecules.

III. The Major Lineages of Life

A. Arranging the diversity of life into the highest taxa is a work in progress

Systematists have traditionally considered the kingdom to be the highest, most inclusive taxonomic category.

- The two kingdom system (animals and plants) long prevailed, but was not suitable as biologists learned more about the structures and life histories of different organisms.
- The five kingdom system was proposed by Robert H. Whittaker (1969) and modified by Lynn Margulis (see also Campbell, Figure 26.9).



Classifying living systems is a work in progress that reflects our increased understanding of the phylogeny of living organisms.

- Using the tools of molecular systematics, biologists have gathered new data that leads them to challenge the traditional five-kingdom system.

- This new information has reopened issues of biological diversity at the highest taxonomic levels. Three alternative classification systems are outlined below (see also Campbell, Figure 26.10):

Six-kingdom system. The prokaryotes are split into two kingdoms based on molecular evidence for an early evolutionary divergence between eubacteria and archaebacteria.

Eubac- teria	Archae- bacteria	Protista	Plantae	Fungi	Animalia

Three-domain system. This scheme assigns more significance to the ancient evolutionary split between eubacteria and archaebacteria by using a superkingdom taxon called the *domain*. The domain Eukarya includes four kingdoms of eukaryotic organisms.

Bacteria	Archaea	Eukarya (Eukaryotes)

Eight-kingdom system. In addition to two separate prokaryotic kingdoms, this system also splits the protists into three kingdoms.

Bacteria	Archaea	Archae- zoa	Chrom- ista	Pro- tista	Plantae	Fungi	Animalia

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