Origin and Evolution of Life on Earth
Bennett & Shostak Chapter 6

HNRS 228 Astrobiology
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Origin and Evolution of Life on Earth - Chapter 6 Overview

- Searching for the origin (6.1)
- Functional beginnings of life (6.2)
  - From chemistry to biology at the molecular level
- Prokaryotes and oxygen (6.3)
- Eukaryotes and explosion of diversity (6.3)
- Mass extinctions, asteroids and climate change (6.4)
- Evolutions of humans (6.5)
- Science in Action: Artificial Life (6.6)

Searching for the origin

- Origin of Life Theories
  - Special Creation
    - Oldest and most widely accepted hypothesis.
  - Extraterrestrial Origin
    - Panspermia - Cosmic material may have carried complex organic molecules to earth.
  - Spontaneous Origin
    - Life evolved from inanimate matter.

Science Searching for the Origin

- Tools and methodologies
  - Principles of physics (e.g., 1st and 2nd Law of TD)
  - Principles of geology (e.g., relative/absolute dating)
  - Principles of chemistry (e.g., chemistry of water)
  - Principles of biology (e.g., key macromolecules)
  - Occam’s razor where appropriate
- Conclusions: plausible scenario of the events and processes that lead to the origin of life

Panspermia

FeS   +   H2S             FeS2   +H2 +   Free Energy

Searching for the Origin: Where on Earth?

- Options
  - Continental landscapes
  - Shallow pools
  - Hot springs
  - Deep sea vents
  - Deep in crust
  - Under frozen seas
- Data to support one or the other
  - Comparative genomics
  - Chemical energy (hydrogen sulfide): FeS + H2S $\rightarrow$ FeS2 + H2 + Free Energy
- Conclusion: deep sea vents
  - Probability of bombardment
Searching for the Origin

- When did life begin?
- Evidence
  - Widespread life forms (3.5 B years ago)
  - Stromatolites (3.5 B years ago)
  - Fossilized cells (3.5 B years ago)
  - Radiometric dating: carbon isotopes (3.85 B years ago)
  - Carbon 12 versus Carbon 13
- Range of dates: 4.1 to 3.85 B years ago
- Conclusions
  - Life arose late in the Hadean Eon
  - Life colonized planet in very short time frame (< 500 M years)

Searching for the Origin: Comparative Genomics

- Comparative morphology versus comparative genomics
- "Living Fossils" of DNA and RNA
  - Sequence of nucleotides in DNA and genome
  - Pattern and process of change in sequences
  - Comparing sequences reveals a pattern/order
- Methodology of comparison - rRNA (ribosomal RNA)

Searching for the Origin: Three Branches of Life Forms

- Results from comparative genomics
  - Three major domains
    - Bacteria
    - Archaea
    - Eukarya
- Common ancestor analysis
- Comparison to organisms today
  - Deep sea volcanic vents
  - Thermophiles (hyperthermophiles)
  - Comparison to environment of Hadean Eon

Life and Atmosphere

- One assumption about the early atmosphere was a reducing atmosphere of carbon dioxide, nitrogen gas, and water vapor, but very little oxygen.
  - Amino acids would therefore not last long.
  - Atmosphere would have changed with the advent of photosynthesis.

Beginnings of Life on Earth

- Organic chemistry*
- Transition from chemistry to biology
- Panspermia
- The evolution of sophisticated features of metabolism and information brokers
- Conclusions

* Enzymes first or TCA or?
iClicker Question

- The origin of life on Earth most likely occurred
  - A before 4.5 billion years ago
  - B between about 4.5 billion years ago and 3.5 billion years ago
  - C between about 3.0 billion years ago and 2.5 billion years ago
  - D between about 2.5 billion years ago and 2.0 billion years ago

iClicker Question

- The first living organisms probably were
  - A cells without nuclei that used RNA as their genetic material
  - B cells with nuclei that used RNA as their genetic material
  - C cells with nuclei that used DNA as their genetic material

Miller-Urey Experiment

- Stanley Miller and Harold Urey (1953) attempted to reproduce conditions at the ocean's edge under a reducing atmosphere.
  - Were able to form amino acids with the addition of lightning to a reducing atmosphere rich in hydrogen and devoid of oxygen.

Significance of and Sequel to Urey Miller Experiment

- Multiple variations of the study (e.g., atmosphere)
  - 20+ amino acids, sugars, bases for DNA and RNA, ATP, etc.
- Significance: scenario for the abiotic formation of key carbon polymers (macromolecules)
  - Probable environments
    - Deep sea vents
    - Tidal pools (role of repeated evaporation and concentration)
    - "evapoconcentration", asteroid bombardment
- Chemical events leading to an "RNA World"
iClicker Question

- The importance of the Miller-Urey experiment is that
  - A it proved beyond doubt that life could have arisen naturally on the young Earth.
  - B it showed that natural chemical reactions can produce building blocks of life.
  - C it showed that clay can catalyze the production of RNA.

Evolutionary Perspective of Enzymes

- Evolutionary advantage of enzymes
  - Specific acceleration of reactions
  - Fitness value: positive
  - Information broker: coded in the DNA
    - Mutation
    - Reproduction
- How did enzymes come to be?

Ribozymes

- What are ribozymes (from ribonucleic acid enzyme)?
  - NOT ribosomes (components of cells where proteins built from amino acids)
  - mRNA (small fragments)
  - Functions
    - Synthesis of RNA, membranes, amino acids, ribosomes
  - Properties
    - Catalytic behavior (enhance rates ~20 times)
    - Genetically programmed
    - Naturally occurring (60-90 bases)

Ribozymes (continued)

- Laboratory studies of ribozymes
  - Creation of RNA fragments at random with existence of enzyme-like properties
  - Variety of enzyme-like properties
    - Cleavage of DNA
    - Cleavage of DNA-RNA hybrids
    - Linking together fragments of DNA
    - Linking together fragments of RNA
    - Transformation of polypeptides to proteins
    - Self-replication (2001)

Summary of Ribozymes

- mRNA fragments
- 3-D conformation like proteins (e.g., fold)
- Functional ribozymes created at random in test tube
- Exhibit catalytic behavior
- Self replicate
- Play a prominent/key role in any scenario for understanding the evolution of life at the biochemical and molecular level
RNA World

Functional Beginnings of Life:
Transition from Chemistry to Biology

• Ribozymes
  - Enzyme activity
  - Self replicating
• Generation of biomacromolecules (C polymers: e.g., sugars, nucleotides, ATP)
  - via abiotic processes on Earth (Urey-Miller)
  - via Panspermia
  - via biotic processes (e.g., ribozymes)
• Role of mutations, natural selection and environment: incremental changes in biomacromolecules that are inherited via RNA and DNA.

Chemical Evolution

• Debated if RNA or Proteins evolved first.
  - RNA Group believes other complex molecules could not have been formed without a heredity molecule.
  - Protein Group argues that without enzymes, replication would not be possible.
  - Peptide-Nucleic Acid Group believes peptide nucleic acid was precursor to RNA.

Evolution of Photosynthesis

$\text{CO}_2 + \text{H}_2\text{O} + \text{Light} = \text{CH}_2\text{O} + \text{O}_2$

• Key processes
  - Absorption of light (pigments)
  - Conversion of light energy into chemical energy (ATP)
  - Synthesis of simple carbon compounds for storage of energy
• Purple bacteria and Cyanobacteria
  - Primitive forms (~3.5 BYA)

iClicker Question

• “RNA world” refers to
  - A the possibility that life migrated from Mars.
  - B the idea that RNA was life’s genetic material before DNA.
  - C the idea that early life was made exclusively from RNA, needing no other organic chemicals.

Ocean Edge Scenario

• Bubble Theory - Bubble structure shielded hydrophobic regions of molecules from contact with water.
  - Alexander Oparin - Primary abiogenesis.
    - Photobionts - Chemical-concentrating bubble-like structures which allowed cells a means of developing chemical complexity.
Prokaryotes

- Microfossils - Earliest evidence of life appears in fossilized forms of microscopic life.
  - Physically resemble bacteria.
  - Prokaryotes - Lack nucleus.
  - Remember Eukaryotes contain nucleus

Archaebacteria - Ancient bacteria that live in extremely hostile conditions.
- Lack peptidoglycan in cell walls.
- Have unusual lipids in cell membranes.
  - Methanogens (microorganisms that produce methane as a metabolic byproduct)
    - Anaerobic
    - Halophiles
    - Thermophiles

Prokaryotes and Atmospheric Oxygen

Evolution of Photosynthesis
\[ \text{CO}_2 + \text{H}_2\text{O} + \text{Energy} = \text{CH}_2\text{O} + \text{O}_2 \]
Evolution of respiration
\[ \text{CH}_2\text{O} + \text{O}_2 = \text{CO}_2 + \text{H}_2\text{O} + \text{Energy} \]
Possibility that respiration is simply the reverse of photosynthesis
Oxygen crisis and the oxygen stimulation to evolution

iClicker Question

The oxygen in Earth's atmosphere was originally released by
- A outgassing from volcanoes.
- B plants.
- C cyanobacteria.
iClicker Question

• Early life arose in an oxygen-free environment, and if any of these microbes had somehow come in contact with molecular oxygen, the most likely effect would have been
  - A nothing at all.
  - B to increase their metabolic rates.
  - C to kill them.

iClicker Question

• Which statement about the Earth’s ozone layer is not true?
  - A It protects us from dangerous solar radiation.
  - B It did not exist when life first arose on Earth.
  - C It first formed a few hundred million years after life colonized the land.

Eukaryotes and an Explosion of Diversity

• Incremental changes in evolution: role of oxygen and diversification of organisms (explain ATP fitness)
• Quantum changes in evolution
  - Symbiosis
  - Lynn Margulis theory: eukaryotes are derived from prokaryotes
  - Compartmentalization and organelles
  - Bacterial origins of chloroplast and mitochondria

Eukaryotes and explosion of diversity

• Eubacteria - Second major bacterial group.
  - Contain very strong cell walls and simpler gene architecture.
  - Cyanobacteria
    - Photosynthetic
    » Appeared at least 3 bya

First Eukaryotic Cells

• First appeared about 1.5 bya. (maybe earlier)
  - Possess internal nucleus.
• Endoplasmic Reticulum - Network of internal membranes in eukaryotes.
  - Both Endoplasmic Reticulum and nuclear membrane are believed to have evolved from infolding in outer bacterial membranes.

Nucleus and Endoplasmic Reticulum Origin

Mitochondria and Chloroplasts

- **Endosymbiotic Theory** suggests a critical stage in the evolution of eukaryotic cells involved endosymbiotic relationships with prokaryotic organisms.
  - Energy-producing bacteria may have come to reside within larger bacteria, eventually evolving into mitochondria.
  - Photosynthetic bacteria may have come to live with larger bacteria, eventually forming chloroplasts in plants and algae.

Sexual Reproduction and Multicellularity

- **Eukaryotic Cells** possess the ability to sexually reproduce.
  - Permits frequent genetic recombination.
- Diversity was also promoted by multicellularity.
  - Fosters cell specialization.

Mass Extinctions, Asteroids and Climate Change

- **Mass extinctions**
  - Dramatic declines in a variety of species, families and phyla (>25%)
  - Timing of decline is concurrent
  - Rate of decline is precipitous (geological sense)
  - Example of catastrophism
- **Best example**
  - Cretaceous/Tertiary boundary (65 M years ago)
  - K-T boundary and Alvarez theory of catastrophism

Mass Extinctions, Asteroids and Climate Change: K-T Boundary

- **Observations**
  - Iridium deposits in distinct layers: suggestion of an asteroid (10-15 Km)
  - Other trace elements (characteristics of asteroids)
  - Shocked quartz
  - Soot deposits
- **Conclusive Evidence**
  - Impact crater 200 km off Yucatan Peninsula (Chicxulub Crater)

Mass Extinctions, Asteroids and Climate Change: Other examples

- **Other mass extinctions**
  - Five major extinctions over last 600 M years
- **Evidence for gradualism**
  - First principles: evolution
  - Pattern in the data
    - Recovery response
    - Overall increment in number of families over geological time
- **Conclusions: Catastrophism coupled with gradualism**

iClicker Question

- The hypothesis that an impact killed the dinosaurs seems
- **A** well supported by geological evidence.
- **B** an idea that once made sense but now can be ruled out.
- **C** just one of dozens of clear examples of impacts causing mass extinctions.
Evolutions of Humans

• Evidence for human evolution
  - Fossils
    • Differences throughout world
    - Out of Africa
    • Increase in brain volume and weight/mass ratio
  - Society
    • Changes in history
  - Civilizations
    • Technological developments

Artificial Life

• What is "artificial life”
• New organisms modified from existing organisms
• New organisms "created" from non-life
• Bioethics of artificial life

iClicker Question

• Which of the following is a likely benefit of creating artificial life?
  - A We'll gain insight into the origin of life on Earth.
  - B The new life could eliminate our dependence on fossil fuels.
  - C The technique could allow us to bring vanished species back to life.

Origin and Evolution of Life on Earth: Conclusions

• Plausible scenarios for the early origin of life on Earth (abiotic and biotic)
• Role of mutation and evolution in origin of increasingly more complex forms of metabolism
• Role of major evolutionary and climatological events as "pulses" of diversification in biota