ASTR 390 Astrobiology

Origins of Complex Life on Earth
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
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
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.
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.
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.
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.
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.
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.
When did life begin?

- Quite early in Earth’s history
- Cannot pinpoint time, but can narrow down a time period with 3 lines of evidence
When did life begin?

- Stromatolites (3.5 bill. Yr)
  - Rocks with distinctive layer structure
- Look identical to living mats of microbes
  - Layers of microbes and sediment
  - Top layer uses photosynthesis
  - Lower layers use top layer’s byproducts
When did life begin?

- Microfossils dating to 3.5 billion years ago
- Difficult to distinguish from mineral structures
- Analysis shows that some structures contain organic carbon
  - found in at least 3 sites
When did life begin?

- Evidence in metamorphic rocks that life existed 3.85 billions years ago
- Low $C^{12}/C^{13}$ fraction in rock layers suggests life
  - Biological processes prefer $C^{12}$ to $C^{13}$
    - Find lower fraction of $C^{13}$
  - Non-biological processes have no preference, so find equal amounts
What is a stromatolite?

- A: A very light-weight sedimentary rock
- B: Igneous rocks that have been infiltrated by bacteria called stroma
- C: Igneous rocks that have proven to be the oldest rocks on the surface of the Earth
- D: Rocks with distinctive layer structure that look identical to living mats of microbes
- E: Rocks with distinctive layer structure formed by alternate igneous and sedimentary rock
When did life begin?

- Rocks before ~4 billion years old are rare and hard to find (think why)
- Time of heavy bombardment ended about 3.8-4.0 billion years ago
  - Last devastating impact between 4.2-3.9 bill. Yr ago
- Evidence suggests life as long as 3.85 billion years ago and definitely at 3.5 billion years ago
- Life rose and dominated the planet between 100-500 million years
Living Fossils

- DNA used as living fossil
- The more alike the DNA sequence between species, the more recent their divergence and extinction of their common ancestor
Living Fossils

- Bacteria and Archaea: genetic material NOT separated from rest of cell
- Eukarya: DNA separated from rest of cell by membrane
- Extremophiles (live near deep-sea vents or in hot springs) closest to root of tree of life
iClicker Question

Why are rocks older than 4 billion years old hard to find on the surface of Earth?

A. The Earth isn’t that old.
B. The Earth is just barely that age so those aged rocks are hard to find.
C. The Earth is considerably older but those age rocks have undergone re-cycling of their carbon with plate tectonics.
D. The Earth is considerably older but the oldest rocks were lost to space through impacts.
E. The Earth didn’t have plate tectonics that long ago so there are no rocks that age present on the surface.
What does the term “living fossil” refer to?

- A fossil that can be brought back to life.
- A fossil that was found in living material.
- The DNA that is common to all living things.
- The RNA that is common to bacteria.
- The DNA that is unique to fossilized remains of animals gone by.
Where did life begin?

- Land is unlikely
  - No $O_2$, no ozone: UV destroys molecular bonds
- Shallow ponds
  - Once favored, full of organic material
  - When evaporated, organic chemical concentration increases making it easier to combine complex molecules leading to life
  - Current experiments indicate lack of chemical energy sufficient to support life
- Deep-sea vents/hot springs
  - DNA evidence suggests that early organisms survived in conditions similar to deep-sea vents
  - Plenty of chemical energy available
How did life begin?

- Simplest organisms today and those dated 3.5 billion years ago are remarkable advanced.
- What are the natural chemical processes that could have led to life?
- Assumptions
  - Life began under chemical conditions of early Earth
  - Life did not migrate to Earth
Organic Chemistry on Early Earth

- In 1920’s, scientists hypothesized that the chemicals in the early atmosphere, fueled by sunlight, would spontaneously create organic molecules
- Tested by Miller-Urey experiment 1950’s
Miller-Urey Experiment

- First flask partially filled with water and heated to produce water vapor (sea)
- Water vapor was moved to a second flask where methane and ammonia vapor was added (atmosphere)
- Electric sparks (lightening) in second flask was energy source for chemical reactions
- Below second flask, water vapor cooled (rain) and recycled to first flask (sea)
- Result: turned brown with amino acids and other complex organic molecules
Time to think......

We have discussed the formation of the solar system and the formation of the terrestrial planets. Now, what is wrong with the Miller-Urey experiment?
Variations of Miller-Urey Experiment

- Different mixes of gases to represent atmosphere
- Different energy sources, like UV (sunlight)

Results: ALL PRODUCE AMINO ACIDS AND COMPLEX ORGANIC MOLECULES

- Not as much as original experiment
- Must be other sources of organic material
Sources of Organic Molecules

- **Chemical reactions in atmosphere**
  - Lab experiments show this is likely

- **Organic material brought by impacts**
  - Chemical analysis of comets and carbonaceous chondrites show that they have organic molecules

- **Chemical reactions near deep-sea vents**
  - Heat from undersea volcano can fuel chemical reactions between water and minerals
Transition from chemistry to biology

- Organic molecules are building blocks of life.
- Low probability of forming life even if repeated several times.
- Intermediate steps of high probability are necessary.
Search for Self-Replicating Molecule

- Work backward from organisms that live today
- DNA is double-stranded = complicated
- RNA obvious candidate, more simple than DNA
  - Hereditary information
  - Can serve as template for replication
  - Fewer steps to produce backbone structure
Search for Self-Replicating Molecule

- Problem: RNA and DNA require enzymes to replicate
- In 1980’s determined that RNA might catalyze their own replication instead of other enzymes
- Early Earth was an RNA-world
Search for Replicating Molecule

- On Early Earth, short strands of RNA-like molecules were produced spontaneously partially or completely.
- RNA-like molecules that could replicate faster with less errors soon dominated population.
- Copying errors introduced mutations, ensuring the production of many variations of successful molecules.
- Allowed molecular evolution to continue.
- RNA-world gave way to DNA-world.
  - DNA less prone to copying errors.
  - DNA more flexible hereditary material.
  - RNA kept some of its original functions.
Assembling Complex Organic Molecules

- Organic soup was too dilute to favor the creation of complex organic molecules
- Lab experiment with possible solution: When hot sand, clay or rock is placed in dilute organic solution, complex molecules self-assemble
  - Organic molecules stick to surface of clay
  - Increases density and likelihood of reactions
  - Strands of RNA up to 100 bases have been produced this way
Assembling Complex Organic Molecules

等症状 inorganic minerals may have also had a similar role

Iron pyrite (fool's gold)
- Positive charges on surface which allows organic molecules to adhere
- Formation of pyrite releases energy which could be used as fuel for chemical reactions
Early Cell-like Structures

- Advantages to enclosing enzymes with RNA molecules
- Close proximity increases rate of reactions between them
- Isolate contents from outside world
Early Cell-like Structures

- Lab experiments suggest that membrane structures existed on early Earth
- Form spontaneously
  - Cool down warm-water solution of amino acids
  - Mix lipids (fats) with water
Nonliving Pre-Cells have Lifelike Behavior

- Grow in size until unstable then split to form a ‘daughter’ cell
- Selectively allow other types of molecules to pass in/out of membrane
- Store energy in the form of electric voltage
Handedness (Chirality)

- Organic molecules come in left- and right-handed forms
- Non-biological processes have not preference
- Biological processes DO have a preference
- If both left- and right-handed RNA developed, why did one die out?
Quick Summary

1. Synthesis of organic precursor molecules
2. Origin of self-replicating RNA
3. Origin of membrane-enclosed pre-cells
4. Origin of true cells with RNA genome
5. Evolution of modern cells with DNA genome
Panspermia?

- Panspermia = life originated elsewhere and migrated to Earth
- Life began in rock, then kicked off the planet by an impact
- Support: organic material is everywhere, and some bacteria can withstand large amounts of radiation and go dormant under low atmospheric conditions
Panspermia

- 2 schools of thought

- School 1: life did not evolve as easily as imagined on early Earth in timescales we've determined

- Problem: entire solar system was under heavy bombardment at the same time

- Other possibility: interstellar migration

- Problem: rock to be ejected out of its own system, then fall into ours and hit the tiny planet of Earth
Panspermia

- School 2: life evolved easily and was everywhere with suitable conditions
- Earth was not first planet with suitable conditions
- Migration of life from another planet (say Mars) dominated before early life on Earth could
  - Could we be Martians?
Panspermia

- Martian meteorites
- Both have possible fossil evidence of life on Mars
  - Not likely
Living cyanobacteria

Microfossils in carbonaceous chondrites
Early Evolution and Rise of $O_2$

- First organisms had simple metabolism
- Atmosphere was $O_2$ free, must have been anaerobic
- Probably chemoheterotrophs
  - Obtained nutrients from organic material
  - Obtained nutrients from inorganic material
    - Modern archaea appear to be close to the root of the tree of life
    - Obtaining energy from chemical reactions involving hydrogen, sulfur and iron compounds (all abundant on early Earth)
Early Evolution

- Natural selection probably resulted in rapid diversification
- Modern DNA has enzymes that reduce the rate of mutations
- RNA is not so lucky, more likely to have copying errors
- Higher mutation rate in early evolution than now
Photosynthesis

- Most important new metabolic process evolved gradually
- Organisms that lived close to ocean surface probably developed means of absorbing sunlight (UV in particular)
- Once absorbed, developed method of turning it into energy
  - Modern organisms of purple sulfur bacteria and green sulfur bacteria much like early photosynthetic microbes, use \( H_2S \) instead of \( H_2O \) for photosynthesis
Photosynthesis

- Using water for photosynthesis developed later, perhaps 3.5 billion years ago
- First appearing in cyanobacteria (blue-green algae)
- By product of $O_2$, released into atmosphere
- Changed the world!
Rise of $O_2$

- $O_2$ is highly reactive
- All initial $O_2$ would react with rock and minerals in water
- $O_2$ could not accumulate in atmosphere until surface rock was saturated
- Rocks 2-3 billion yr old called banded iron formations, show atmosphere had <1% of current amount of $O_2$
- Rock evidence suggests that $O_2$ amounts in atmosphere began to rise about 2.0 billion yr ago
- Clear evidence of $O_2$ near current levels appears only 200 million yr ago
  - Find charcoal (fossil fuel)
  - Indicates enough $O_2$ in atmosphere for fires to burn
Rise of $O_2$

- Rise of $O_2$ would have created a crisis for life
- $O_2$ reacts with bonds of organic materials
- Surviving species avoided effects of $O_2$ because they lived or migrated to underground locations
  - Many anaerobic microbes found in such locales today
Early Eukaryotes

- Fossil evidence dates to 2.1 billion years ago.
- Dates to when $O_2$ rising in atmosphere.
- DNA evidence suggests that prokaryotes and eukaryotes separated from common ancestor much earlier.
- $O_2$ played a key role in eukaryote evolution:
  - Cells can produce energy more efficiently using aerobic metabolism than anaerobic metabolism.
  - Adaptations of aerobic organisms could develop adaptations that required more energy that would be available for anaerobic organisms.
The Cambrian Explosion

- Animal branch of the tree of life
- Different classifications based on body plan
- All known body plans made appearance in fossil record in a time span of 40 million years
  - <1% of Earth’s age
  - Animal diversity began 545 mill. Yr ago
Colonization of Land

- Life flourished where liquid water exist
- Life on land was more complicated
  - Had to develop means of collecting solar energy above ground and nutrients below
- Life in shallow ponds or edges of lakes
  - Water evaporates
  - Natural selection favored that which could withstand periods of drought
Colonization of Land

DNA evidence suggests that plants evolved from an algae.

It took only 75 mill. Yrs for animals to follow plants out of water.
Mass Extinctions

![Graph showing percent extinction over time before present (millions of years)]
Mass Extinctions

Possible Causes

- Impacts
  - Impact sites found for K-T boundary
  - Suspected for Permian extinction 245 mill yr ago

- Active volcanism
  - Climate change

- External influence for copying errors
  - Increase in solar particles or radiation hitting surface
  - Local supernova
Primate Evolution

- Monkeys, apes, lemurs and humans have a common ancestor that lived in trees
- Tree life
  - Limber arms for swinging between branches
  - Eyes in front of head for depth perception
  - Offspring would be born more helpless than other animals
Emergence of Humans

- Did NOT evolve from gorillas or monkeys
- Share a common ancestor that lived just a few million years ago
- 98% of human genome is identical to genome of the chimpanzee
- 2% difference in genome separates the success of humans verses chimps
  - Also indicates evolution of intelligence is complex
Emergence of Humans
Emergence of Humans

- After hominids diverged from chimps and gorillas, evolution has followed a complex path.
- Numerous hominids species existed, some during the same time period.
  - All humans are the same species.
- First skull fossils that are identical to modern human skulls dates to 100,000 yr old.
- Our ancestors shared the Earth with Neanderthals.
  - Went extinct 35,000 years ago.
Emergence of Humans
Cultural and Technological Evolution

- Have not undergone major biological evolution in 40,000 years
  - Mutation rates are slow
- Dramatic cultural changes
  - Transmission of knowledge between generations
    - Spoken to written word, thousands of years
    - Agriculture
- Technological evolution
  - Result of coupling between science and technology
  - About 100 years between industrial revolution to landing on the Moon and generating weapons of mass destruction