FORMATION OF THE EARTH

- FORMED (ALONG WITH THE SUN AND THE REST OF THE SOLAR SYSTEM) OUT OF A NEBULA 4.6 BILLION YEARS AGO

- VERY HOT INITIALLY DUE TO “HEAT OF FORMATION”

- MOLTEN AT FIRST, DIFFERENTIATED (SEPARATED INTO LAYERS), THEN COOLED & SOLIDIFIED

- NO ATMOSPHERE INITIALLY – HOT ENOUGH THAT GAS MOLECULES WERE MOVING FAST ENOUGH TO ESCAPE FROM EARTH'S GRAVITY

- ATMOSPHERE AND WATER ADDED LATER VIA OUTGASSING AND COMETARY IMPACTS
BOMBARDMENT

- Earth (and other planets and moons) bombarded by leftover planetesimals, producing impact craters

- Many craters still visible on Earth’s moon and some other inner planets

- On Earth, most craters were eventually eroded away by water and wind, or erased by subduction

- Impacts of comets and asteroids added most light elements (hydrogen, carbon, nitrogen, and oxygen), water, and perhaps organic molecules
FORMATION OF EARTH’S MOON

- No other inner planet has a large moon.
- Less dense than Earth, no iron core.
- Fewer volatiles (easily vaporized materials).
- Composition resembles that of Earth’s mantle.
- Condensation from solar nebula next to Earth would produce object of same composition as Earth, including an iron core.
- Current accepted theory - Mars-size object collided with Earth in the first 100 million years, material thrown into Earth orbit, then condensed to form moon.
- Moon was bombarded by debris, forming craters and Maria (large impact craters flooded by molten rock that then solidified, leaving a smooth flat plain).
ATMOSPHERE AND OCEANS FORMED VIA:
- BOMBARDMENT BY COMETS AND ASTEROIDS
- OUTGASSING (RELEASE OF GAS PREVIOUSLY TRAPPED INSIDE ROCK) FROM VOLCANOES

EARLY ATMOSPHERE WAS VERY DIFFERENT FROM CURRENT ATMOSPHERE
- CONSISTED MOSTLY OF CARBON DIOXIDE ($\text{CO}_2$), CARBON MONOXIDE (CO), NITROGEN ($\text{N}_2$), AND WATER VAPOR ($\text{H}_2\text{O}$)
- NO OXYGEN
- CURRENT ATMOSPHERE IS MOSTLY NITROGEN ($\text{N}_2$) AND OXYGEN ($\text{O}_2$)
RELATIONSHIP BETWEEN TEMPERATURE, SPEED, AND MASS OF A MOLECULE

- Recall that the higher the temperature, the faster the molecules are moving.

- However, the mass of a molecule also affects how fast it's moving.

- Consider a mixture of molecules (e.g., the air in this room), all at the same temperature:
  - Lighter molecules move faster.
  - Heavier molecules move more slowly.
DEVELOPMENT OF ATMOSPHERE

- Ultraviolet (UV) radiation from the sun broke apart many molecules into atoms.  
  - Example: Water broke apart into hydrogen and oxygen.

- Hydrogen (H and H₂) escaped to space.  
  - Earth’s gravity wasn’t strong enough to hold onto such light fast-moving objects.

- Oxygen atoms combined to form small amounts of oxygen (O₂) and ozone (O₃) molecules.  
  - Ozone protects the Earth's surface from UV radiation, which would otherwise break apart many large organic molecules.
DEVELOPMENT OF ATMOSPHERE

- MOST CARBON DIOXIDE ($CO_2$) WAS PULLED OUT OF THE ATMOSPHERE AND INCORPORATED INTO CARBONATE ROCKS.
  - THIS PROCESS WAS ACCELERATED BY LIFE, ONCE IT GOT STARTED.

- CYANOBACTERIA (EARLY FORM OF LIFE) RELEASED LARGE AMOUNTS OF OXYGEN INTO THE ATMOSPHERE.

- THE EARTH'S ATMOSPHERE WAS CHANGED DRASTICALLY BY THE PRESENCE OF LIFE!
TODAY’S ATMOSPHERE

- 78 % NITROGEN (N\textsubscript{2})
- 21 % OXYGEN (O\textsubscript{2})
- 1% ARGON (Ar)
- 0.01 % CARBON DIOXIDE (CO\textsubscript{2})

- PLANTS TAKE IN CO\textsubscript{2} AND RELEASE O\textsubscript{2}
- ANIMALS TAKE IN O\textsubscript{2} AND RELEASE CO\textsubscript{2}
- THE EFFECTS OF ANIMALS AND PLANTS COMPENSATE FOR EACH OTHER TO KEEP THE AMOUNTS OF O\textsubscript{2} AND CO\textsubscript{2} ROUGHLY CONSTANT.
LIFE AND THE ATMOSPHERE

- LIFE ON EARTH ORIGINATED IN AN ATMOSPHERE CONTAINING LITTLE OR NO OXYGEN.

- LIVING THINGS THEN CHANGED THE ATMOSPHERE, ADDING LARGE AMOUNTS OF OXYGEN.

- IN AN ATMOSPHERE CONTAINING OXYGEN, COMPLEX ORGANIC MOLECULES CANNOT FORM. OXYGEN INTERACTS WITH THEM AND BREAKS THEM APART.
CLIMATE

- Sun has gotten a little brighter over time → warming
- Tilt of Earth’s axis has changed a little with time → changes in severity of seasons
- CO₂ cycle (described in text) regulates the Earth’s climate, prevents extreme changes
- Variations in global climate have produced ice ages and “snowball Earth” periods (early very severe ice ages)
- Greenhouse effect has caused warming
GREENHOUSE EFFECT

SUNLIGHT (MOSTLY VISIBLE LIGHT) IS ABSORBED BY A PLANET’S SURFACE.

- ENERGY IS RE-RADIATED FROM THE GROUND (WHICH ACTS AS A BLACKBODY), MOSTLY AS INFRARED RADIATION.

- INFRARED RADIATION IS ABSORBED BY ATMOSPHERIC “GREENHOUSE GASES.”

- GREENHOUSE GASES ARE CO₂, H₂O, CH₄, AND OTHERS (MOLECULES WITH 3 OR MORE ATOMS).
GREENHOUSE EFFECT

- Atmosphere warms up as a result of absorbing infrared radiation from the ground.
- Atmosphere therefore radiates (as a blackbody) more radiation to space.
- Eventually equilibrium is reached so that the rate at which energy absorbed = the rate at which energy radiated, and temperature stabilizes.
- Final temperature is hotter than it would be without absorption of infrared radiation by atmospheric greenhouse gases.
GREENHOUSE EFFECT

- Because of the greenhouse effect, Earth is 40K (or 40°C or 72°F) hotter than it would be otherwise.

  - Human industrial activity is adding more greenhouse gases to Earth’s atmosphere.

  - “Global warming” (an increase in average planet-wide temperatures over the last century or so) has been measured and is really happening.

  - The scientific evidence is overwhelming that human activity is in large part responsible for global warming.

  - Claims to the contrary are probably “wishful thinking” or politically motivated.
WHEN DID LIFE BEGIN?

- PROBABLY BETWEEN 3.9 AND 4.2 BILLION YEARS AGO
- THIS WAS 0.4 TO 0.7 BILLION YEARS (OR 400 TO 700 MILLION YEARS) AFTER THE EARTH FORMED.
- COMPARED TO THE CURRENT AGE OF THE EARTH (4.6 BILLION YEARS), NOT MUCH TIME ELAPSED BEFORE LIFE STARTED.
- LIFE GOT STARTED VERY QUICKLY AFTER THE EARTH FORMED!

EVIDENCE FOR EARLY LIFE:
- ANCIENT MICROFOSSILS
- STROMATOLITES
- ISOTOPIC ABUNDANCES OF CARBON
EVIDENCE FOR EARLY LIFE FROM FOSSIL RECORD

- THERE ISN'T A LOT BECAUSE:
  - EARLY SIMPLE ORGANISMS HAVE NO HARD PARTS THAT FOSSILIZE EASILY.
  - OLD SEDIMENTARY ROCKS ARE RARE.
    - MOST HAVE BEEN DESTROYED VIA SUBDUCTION, EROSION, OR REPROCESSING INTO METAMORPHIC ROCKS.

- NEVERTHELESS, FOSSILIZED INDIVIDUAL CELLS (MICROFOSSILS) AS OLD AS 3.2 TO 3.5 BILLION YEARS HAVE BEEN FOUND.
  - HARD TO DISTINGUISH FROM MINERAL STRUCTURES
  - ALREADY LOOK SUFFICIENTLY COMPLEX THAT THEY PROBABLY WEREN'T THE EARLIEST LIFE
OTHER EVIDENCE

STROMATOLITES

– CERTAIN TYPES OF LAYERED ROCKS
– LOOK A LOT LIKE FOSSIL VERSIONS OF COLONIES OF MICROBES THAT STILL EXIST
– MICROBES ALREADY QUITE ADVANCED (SOME CARRY OUT PHOTOSYNTHESIS), IMPLYING LIFE HAD ALREADY BEEN AROUND FOR A WHILE.
– ROCKS ARE ABOUT 3.5 BILLION YEARS OLD.

RELATIVE ABUNDANCES OF CARBON ISOTOPES INDICATE LIFE IN ROCKS THAT ARE UP TO 3.85 BILLION YEARS OLD

– REMAINS OF LIVING ORGANISMS HAVE SLIGHTLY LESS $^{13}$C COMPARED WITH $^{12}$C THAN OTHER MATERIALS.
– THIS HAPPENS BECAUSE $^{12}$C IS MORE EASILY METABOLIZED BY LIVING ORGANISMS THAN $^{13}$C.
MULTIPLE ORIGINS OF LIFE?

- Earth was heavily bombarded by comets and asteroids (left over from solar system formation) until 3.9 billion years ago.

- Life may have gotten started as early as 4.4 or 4.5 billion years ago (very soon after Earth cooled enough for crust to solidify).

- A sufficiently large impact could have wiped out all life on Earth.

- Life may have gotten started, then been wiped out, several times.
HOW DID LIFE BEGIN?

- SIMPLE ORGANIC MOLECULES (MONOMERS) WERE PRODUCED VIA CHEMICAL REACTIONS AND/OR DELIVERED VIA COMETARY IMPACTS.

- SIMPLE ORGANIC MOLECULES COMBINED TO MAKE LONG POLYMERS

- SOME OF THE LONG POLYMERS MUST HAVE BEEN SELF-REPLICATING (LIKE DNA).

- POLYMERS WERE ENCLOSED INSIDE A “CELL” THAT WAS SEPARATED FROM ITS ENVIRONMENT BY A MEMBRANE.
**WHERE DID LIFE BEGIN?**

- **PROBABLY NOT ON DRY LAND**
  - UV RADIATION (NO OZONE LAYER YET), IMPACTS, OR OTHER ENVIRONMENTAL HAZARDS WOULD MOST LIKELY HAVE WIPED IT OUT
  - HARD FOR MOLECULES TO REACT WITH EACH OTHER ENOUGH TO PRODUCE LONG POLYMERS UNLESS DISSOLVED IN A LIQUID

- **POSSIBILITIES:**
  - OCEANS NEAR HYDROTHERMAL VENTS
  - HOT SPRINGS
  - SMALL POOLS OF WATER (TIDEPOOLS?)
  - INSIDE ROCKS

- **MAYBE LIFE WAS DELIVERED TO EARTH FROM AN EXTRATERRESTRIAL SOURCE, AS OPPOSED TO HAVING ORIGINATED HERE.**
PANSPERMIA THEORY OF ORIGIN OF LIFE

THE “SEEDING” OF LIFE ON EARTH FROM AN EXTRATERRESTRIAL SOURCE (ARRHENIUS, 1907)

HOW IT WAS PROPOSED TO WORK:

• SMALL ORGANISMS ARE PRESENT IN THE UPPER ATMOSPHERE OF A “SOURCE” PLANET.

• SMALL ORGANISMS COULD BE BLOWN OUT OF THE ATMOSPHERE AND INTO SPACE BY THE PRESSURE OF SUNLIGHT.

• FOR THIS TO WORK, ORGANISMS MUST BE THE SIZE OF BACTERIA, SPORES, OR VIRUSES.

• ALTERNATIVELY, AN IMPACT COULD HAVE THROWN ORGANISMS (MAYBE INSIDE ROCKS) INTO SPACE.

BUT HOW DID LIFE START ON THE “SOURCE” PLANET? THE QUESTION OF THE ULTIMATE SOURCE OF LIFE IS NOT ANSWERED BY THIS THEORY!
• IS THE “SOURCE” PLANET A NEARBY PLANET IN OUR SOLAR SYSTEM (LIKE MARS OR VENUS) OR A PLANET IN ANOTHER SOLAR SYSTEM?

• PROBABLY NOT A PLANET IN ANOTHER SOLAR SYSTEM BECAUSE:

• TRIP TO EARTH WOULD TAKE MILLIONS OR BILLIONS OF YEARS, AND DURING THIS TIME:
  • ORGANISMS WOULD LIKELY BE ERODED AWAY BY COLLISIONS WITH GAS AND DUST IN SPACE.
  • ORGANISMS WOULD LIKELY BE KILLED BY EITHER ULTRAVIOLET LIGHT FROM STARS OR COSMIC RAYS.

• EARTH IS SO FAR FROM “SOURCE” PLANET THAT THE CHANCES OF THE ORGANISMS HAPPENING TO HIT THE EARTH ARE VERY SMALL.
  • STATISTICALLY, A LARGE NUMBER OF “SOURCE” PLANETS ARE REQUIRED TO PROVIDE EARTH WITH EVEN ONE ORGANISM.
· IS THE “SOURCE” PLANET A NEARBY PLANET IN OUR SOLAR SYSTEM (LIKE MARS OR VENUS) OR A PLANET IN ANOTHER SOLAR SYSTEM?

· COULD POSSIBLY BE A NEARBY PLANET IN OUR SOLAR SYSTEM
  
  · WE KNOW THAT ROCKS HAVE BEEN BLASTED OFF THE SURFACE OF THE MOON, MARS, AND VENUS BY IMPACTS, TRAVELED THROUGH SPACE, AND LANDED AS METEORITES ON THE EARTH.
  
  · TRIP TO EARTH COULD TAKE ANYWHERE FROM A FEW YEARS TO A FEW MILLION YEARS.
  
  · SIMPLE LIFE FORM MIGHT BE ABLE TO SURVIVE A TRIP OF A FEW YEARS.

**********

EVEN MORE LIKELY: SIMPLE ORGANIC MOLECULES (BUT NOT ACTUAL ORGANISMS) WERE DELIVERED TO THE EARLY EARTH VIA IMPACTS OF COMETS AND ASTEROIDS.
HYDROTHERMAL VENTS

- ALSO KNOWN AS BLACK SMOKERS
- LOCATED ON OCEAN FLOOR AT MID-OCEAN RIDGES WHERE TECTONIC PLATES SPREAD APART
- VERY HIGH TEMPERATURE AND PRESSURE
- SPEW OUT HOT WATER CONTAINING MANY DISSOLVED MINERALS
- PROVIDE A SOURCE OF RAW MATERIALS AND ENERGY FOR A RICH DIVERSITY OF LIFE (EXTREMOPHILES)
EXTREMOPHILES

- ORGANISMS THAT LIVE IN ENVIRONMENTS THAT WOULD BE LETHAL TO MOST LIFE FORMS:
  - NEAR HYDROTHERMAL VENTS (HIGH TEMPERATURE AND PRESSURE)
  - IN HOT SPRINGS (HIGH TEMPERATURE AND PRESSURE)
  - DRY VALLEYS OF ANTARCTICA (COLD AND DRY)
  - INSIDE ROCKS BELOW EARTH’S SURFACE
  - ENVIRONMENTS WHERE CHEMICALS THAT ARE POISONOUS TO MOST OTHER ORGANISMS ARE PRESENT

- MOST ARE SINGLE-CELLED ORGANISMS.

- MANY OBTAIN ENERGY AND/OR RAW MATERIALS FROM INORGANIC CHEMICAL SOURCES.
  - MOST OTHER ORGANISMS OBTAIN ENERGY AND RAW MATERIALS FROM ORGANIC CHEMICAL SOURCES (i.e., FOOD) OR SUNLIGHT
EXTREMOPHILES

- THEIR EXISTENCE SUGGESTS THAT LIFE CAN BE FOUND IN A WIDE VARIETY OF ENVIRONMENTS.

- KEEP THIS IN MIND IN EXAMINING POSSIBLE LOCATIONS FOR EXTRATERRESTRIAL LIFE.

- HOWEVER, ONCE LIFE GETS STARTED, IT MIGHT BE ABLE TO ADAPT TO ENVIRONMENTS IN WHICH IT COULD NOT HAVE ORIGINATED.
DID LIFE BEGIN AT HYDROTHERMAL VENTS?

**PRO:**
- ENVIRONMENT NOT AFFECTED MUCH BY IMPACTS (UNLESS OCEAN VAPORIZES COMPLETELY), UV RADIATION, AND OTHER ENVIRONMENTAL HAZARDS ON EARLY EARTH
- ORGANIC MOLECULES CAN INTERACT & LINK TOGETHER TO MAKE LARGER MOLECULES MORE EASILY IF DISSOLVED IN WATER
- DNA EVIDENCE IS SUGGESTIVE OF THIS

**CON:**
- VENT LIFETIME SHORT (FEW CENTURIES)
- ORGANIC MATERIALS QUICKLY DILUTED IN SEAWATER
- MAYBE TOO HOT

**BOTTOM LINE:** SEEMS LIKE A GOOD POSSIBILITY
DID LIFE BEGIN IN SMALL POOLS OF WATER (MAYBE TIDEPOLLS)?

**PRO:**

- Organic molecules can interact & link together to make larger molecules more easily if dissolved in water.
- In a small body of water, chemicals can become more concentrated than in a large body of water like an ocean (especially as pool evaporates).
- Tides occasionally bring in new materials into tidepools.
- Solid substrate at the bottom of the pool could aid in lining up monomers to form polymers, and selecting one handedness (isomer) of molecules.

**CON:**

- Small amount of water doesn't provide enough protection from environmental hazards like impacts and UV radiation.
- May not be enough energy available.
MILLER-UREY EXPERIMENTS

- ATTEMPTS TO CREATE LIFE IN THE LABORATORY
- PROVIDE A MIXTURE OF GASES SIMILAR TO THAT IN THE EARLY ATMOSPHERE
- PROVIDE WATER TO SIMULATE OCEANS OR POOLS
- PROVIDE A SOURCE OF ENERGY
- WAIT AND SEE WHAT HAPPENS
INGREDIENTS FOR MILLER-UREY EXPERIMENTS

WATER

GASES:

- $\text{H}_2\text{O}$ (WATER VAPOR)
- $\text{CO}_2$ (CARBON DIOXIDE)
- $\text{N}_2$ (NITROGEN)
- $\text{H}_2$ (HYDROGEN)
- $\text{CH}_4$ (METHANE)
- $\text{NH}_3$ (AMMONIA)

ENERGY:

- HEAT
- ELECTRIC SPARK (LIGHTNING)
- ULTRAVIOLET LIGHT

TIME (WAIT A FEW DAYS TO WEEKS)
Primordial Atmosphere
Raw materials
\( \text{H}_2\text{O}, \text{CO}_2, \text{N}_2, \text{H}_2 \)

Electric sparks
Organic molecules produced

Condenser, maintained at low temperature

Boiling water

Organic molecules accumulate in U-tube
RESULTS

MANY ORGANIC MOLECULES ARE PRODUCED, INCLUDING:

- **SUGARS** (INCLUDING RIBOSE)
- **FATS OR LIPIDS**
- **AMINO ACIDS** (50% L AND 50% D)
- **GENETIC BASES**

**NOTE:** IF OXYGEN IS PRESENT, THESE MOLECULES ARE NOT FORMED!!

(IF OXYGEN IS PRESENT, EVERYTHING ➔ CO₂ & H₂O)
LIMITATIONS

- NOT ALL IMPORTANT ORGANIC MOLECULES ARE FORMED

  - NO LIVING ORGANISMS ARE FORMED

- WHY?
  - MAYBE MORE TIME IS NEEDED (MILLIONS OF YEARS, NOT JUST A FEW WEEKS OR MONTHS)
  - MAYBE SOME KEY INGREDIENT IS MISSING
  - MAYBE BASIC IDEA IS WRONG
SOURCES OF SIMPLE ORGANIC MOLECULES ON EARLY EARTH

- MILLER-UREY TYPE REACTIONS IN
  - SMALL POOLS OF WATER
  - OCEANS NEAR HYDROTHERMAL VENTS
  - OTHER LOCATIONS?

- DELIVERY VIA COMET AND ASTEROID IMPACTS

- THESE PROBABLY ALL PLAYED A ROLE

- BUT THIS ISN’T LIFE YET!

- WHAT HAPPENED NEXT?
HOW DID SIMPLE ORGANIC MOLECULES (MONOMERS) JOIN UP TO MAKE LONG POLYMERS?

IF IMMERSED IN A LIQUID, THEY CAN MOVE AROUND AND COMBINE MORE EASILY.

THIS WORKS BETTER IF THEY ARE CONCENTRATED, AS IN A SMALL POOL.

THEY MAY HAVE ORGANIZED THEMSELVES ON SURFACES OF CLAY.

- THIS REQUIRES A SOLID SUBSTRATE, SUCH AS THE BOTTOM OF A BODY OF WATER.
- MONOMERS WILL STICK TO THE SURFACE.
- THE SURFACE MAY HELP THE MONOMERS LINE UP PROPERLY TO LINK TOGETHER.
- THIS MAY HAVE ALSO SELECTED ONE HANDEDNESS.
PROTEINS, DNA, AND RNA

DNA AND RNA CAN REPLICATE THEMSELVES (AN IMPORTANT CHARACTERISTIC OF LIFE).

IN MODERN LIVING ORGANISMS, DNA AND PROTEINS INTERACT IN IMPORTANT WAYS.

– INSTRUCTIONS FOR CONSTRUCTING PROTEINS ARE CARRIED IN DNA.

– PROTEINS ARE IMPORTANT IN CONSTRUCTING DNA. (SOME ARE NEEDED FOR DNA REPLICATION).

PROBLEM: WHICH CAME FIRST?

POSSIBLE SOLUTION: RNA MAY HAVE PRECEDED DNA AS GENETIC MATERIAL IN EARLIEST LIFE FORMS (LIKE IN SOME MODERN VIRUSES). RNA CAN PLAY THE ROLES OF BOTH DNA AND PROTEINS. AT SOME POINT, A “MISTAKE” IN RNA REPLICATION RESULTED IN DNA BEING PRODUCED.
ORIGIN OF CELLS

- ALL LIFE ON EARTH OF MADE OF CELLS.
- A CELL IS SEPARATED FROM ITS ENVIRONMENT BY A MEMBRANE.
- ORGANIC MOLECULES ARE KEPT CLOSE TOGETHER, MAKING IT EASIER FOR THEM TO INTERACT, IF ENCLOSED INSIDE A CELL
- EXPERIMENTS SUGGEST HOW CELLS MAY HAVE ORIGINATED:
  - ORGANIC POLYMERS DISSOLVED IN WATER CAN EASILY GROUP TOGETHER INTO DROPLETS WHEN COOLED.
  - MEMBRANES FORM EASILY UNDER MANY CONDITIONS.
  - CLAY SURFACES ALSO CAN HELP MEMBRANES TO FORM.
  - EXPERIMENTS WITH CLAY SURFACES AT THE BOTTOM OF A POOL OF WATER HAVE PRODUCED “PRE-CELLS” - A DROPLET ENCLOSED BY A MEMBRANE WITH RNA INSIDE!