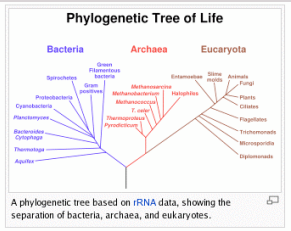


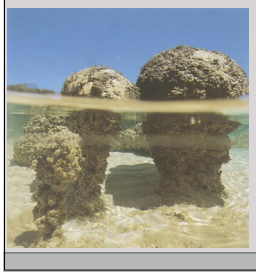
When did critical events in the evolution of life on Earth occur?

Most dates more than about 1 billion years ago are based on indirect evidence - can be disputed…

- prokaryotes
- eukaryotes
- multicellular organisms
- intelligent life

Prokaryotes

Single celled organisms (bacteria and archaea) that lack cell nucleus and other `organization' within the cell



Isotopic evidence + rock beds called *stromatolites* suggest that the simplest life may have started 3.5 - 3.8 billion years ago

About the time the Late Heavy Bombardment on the Moon ended

Prokaryotes have much more diverse metabolic pathways than more complex organisms

- **anaerobic** - do not require oxygen… necessary since the early atmosphere was oxygen poor
- can derive energy from reactions involving heat, inorganic materials such as hydrogen, sulphur etc
- photosynthesis probably developed early, but did not initially use water and did not yield oxygen as a byproduct

Eukaryotes

Single or multicellular organisms that have cell nuclei and complex internal structures (e.g. mitochondria)

May have arisen from symbiosis - beneficial relation between initially separate prokaryotic organisms that eventually fused

Cell nuclei date to at least 2.1 billion years ago (but possibly older)

Multicelled organisms date to ~1.2 billion years ago

Genetic complexity

Mycoplasma genitalium: 0.58 million base pairs (100% coding)

E. coli: 4.8 million base pairs (100%)

Some simple eukarya: 10-100 million base pairs

Homo sapiens: 3.4 billion base pairs

Wheat: 17 billion
Amoeba: 670 billion

Atmospheric composition on Earth

Current atmosphere of Earth:
- nitrogen N_2: 78%
- oxygen O_2: 21%
- argon, water vapor, trace amounts of other species

Oxygen is a reactive gas, and its abundance can be deduced from geological evidence

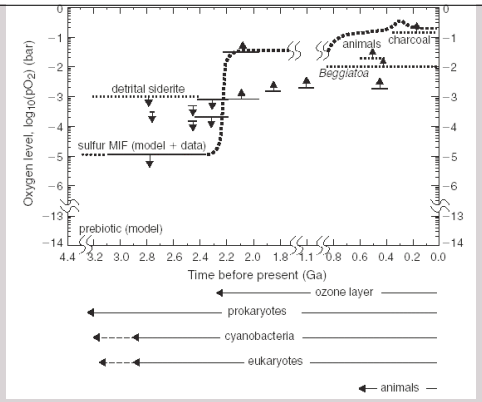
Source: photosynthesis of modern plants

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

Sinks: respiration, decay, inorganic reactions

Timescale for the sinks to remove O_2 from the atmosphere is *extremely* short - about 2 million years

Substantial oxygen atmosphere exists because some carbon avoids reacting with oxygen by becoming buried in sediments

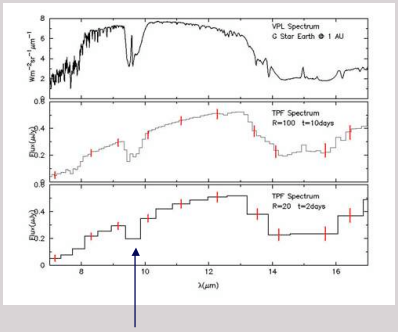


Increase in the O_2 content of atmosphere ~2.4 billion years ago may reflect:

- first organisms that released O_2 as byproduct of photosynthesis
- epoch when O_2 production became large enough to overwhelm oxygen sinks

Implications for detecting life on extrasolar planets:

- presence of O_2 or O_3 is an indicator of life
- absence of oxygen does not prove that life does not exist - for more than half Earth's history our atmosphere was oxygen free



spectral signature of ozone in the mid infrared

How significant are catastrophic events?

Asteroid impacts

Major climate change

Development of an oxygen atmosphere

Mass extinctions driven by sudden changes to the Earth may have promoted subsequent diversity

c.f. Stephen Jay Gould's book `Wonderful Life''

Generalizing to other habitable planets

If we accept the ordering:

- prokaryotic organisms @3.5 billion years ago
- eukarya @2.1 billion years ago
- multicellular life @1.2 billion years ago

Inference:

Simplest forms of life arose almost as quickly as possible on Earth - recall that heavy bombardment of the Earth continued till ~4 billion years ago

BUT - several billion years were needed before any `complex' life forms arose

One interpretation of this data:

Probability (ease) of life developing on a habitable world (liquid water, energy) is high

Probability of complex life arising from evolution of simple life is unclear, but might be small

Limitation: only one example! If the probability of life getting started is high, it probably happened independently more that once - but no evidence of that survives

A more pessimistic view is also logically tenable:

- suppose the probability of life developing (say per billion years) is very small - 1 in a million
- suppose the probability of complex life developing is similarly small

In this case, *on a planet that has intelligent life*, it is likely that simple life arose unusually early

The early appearance of life on Earth may not imply that lie starts easily - impossible to say for sure without additional evidence