Life on Earth

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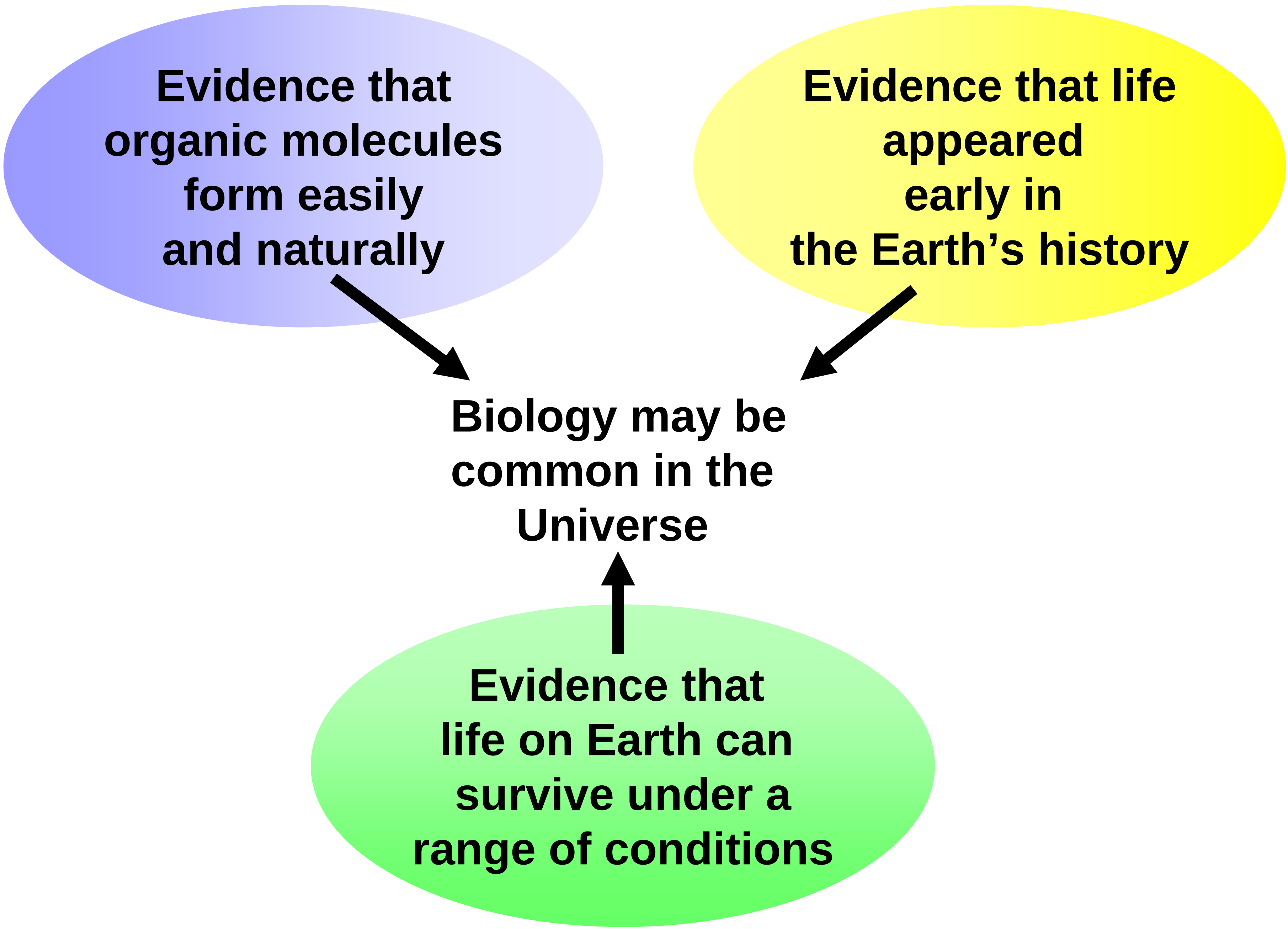
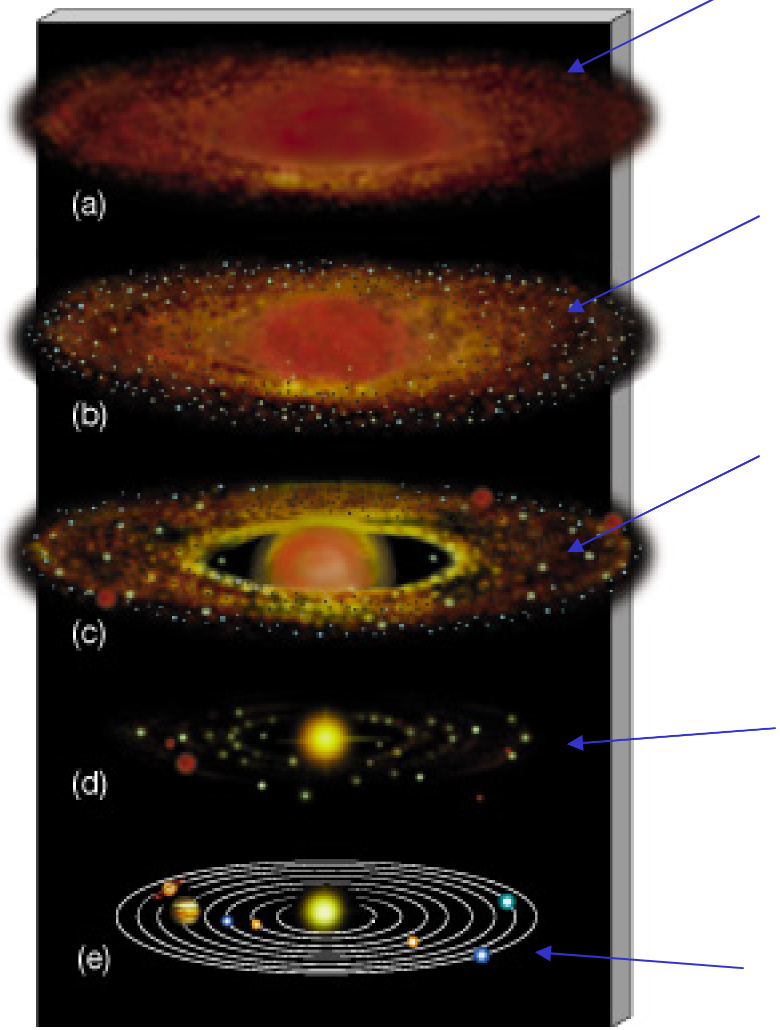
Life in the Cosmos: Jan 2006


Evidence that organic molecules form easily and naturally
Evidence that life appeared early in the Earth's history
Biology may be common in the Universe
Evidence that life on Earth can survive under a range of conditions

Stages in the formation of the solar system



(a) The solar nebula after it has contracted and flattened to form a spinning disk

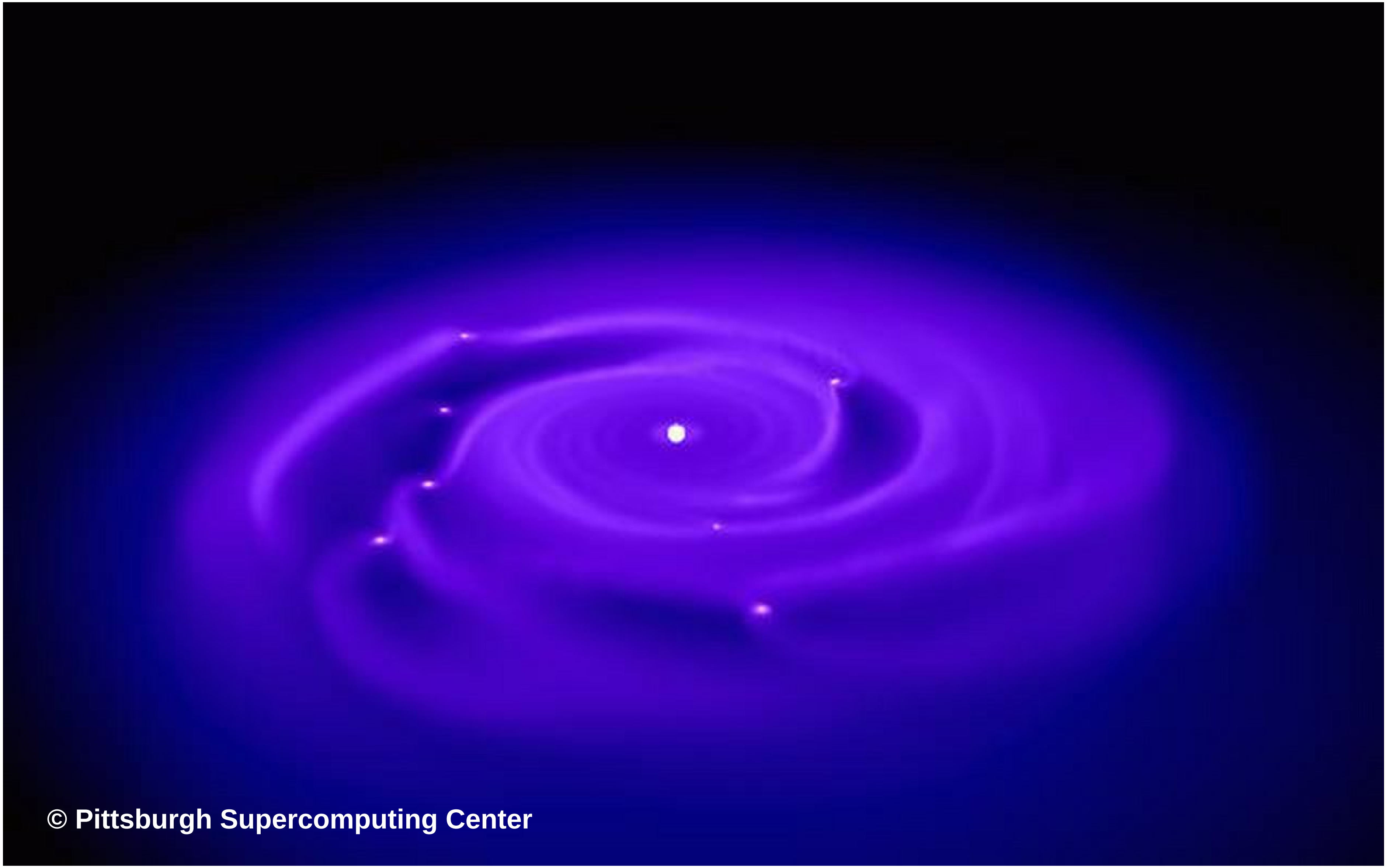
(b) Dust grains act as condensation nuclei, forming clumps of matter that accrete into *planetesimals.*

(c) Strong outflows from the still-forming Sun blow away the nebular gas. Large planetesimals in the outer solar system have begun to form

(d) Planetesimals continue to collide and grow. The gas giant planets are already formed.

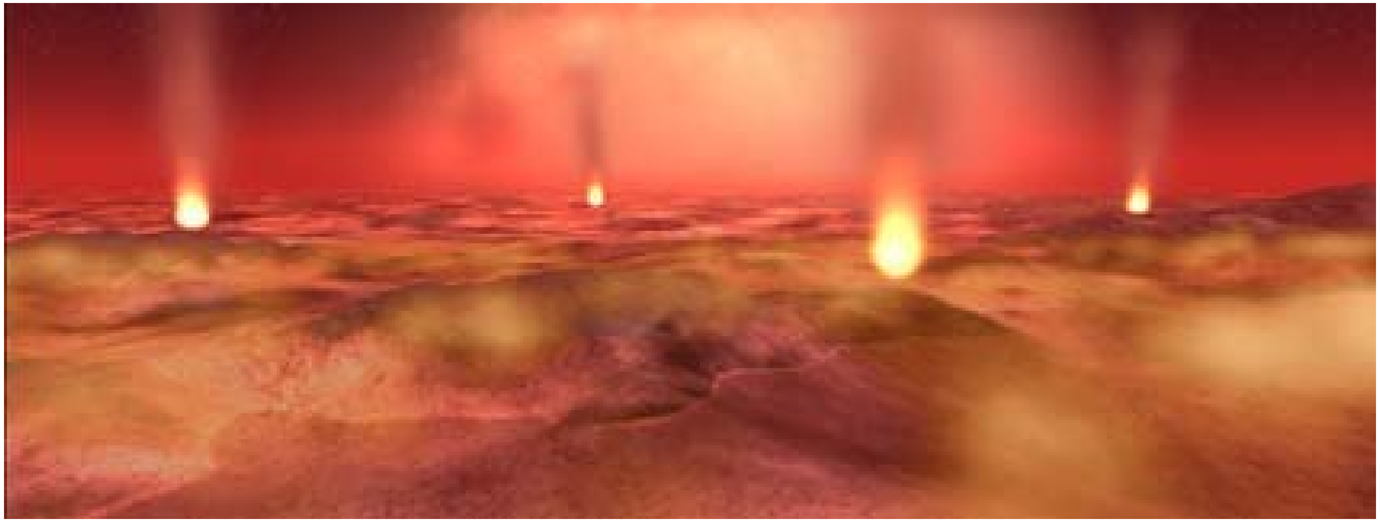
(e) Over the course of ~ a hundred million years, planetesimals form into a few large planets, or are ejected from solar system. Solar radiation ‘blows away’ remaining dust

Numerical experiments suggest planet formation may take only ~ 1000 years!



The Hadean Era – When Impacts Ruled the Earth

- The period starting with formation of the oldest solar system material (4.56 Byr ago) and ending with the date of the oldest Earth rocks still in existence (3.8 - 4 Byr ago) is called the *Hadean Era*



- During this time, Earth was very hot, volcanically active, and was undergoing frequent impacts from planetesimals

Earth's Atmosphere in the Hadean Era

- The Hadean atmosphere was dominated by carbon dioxide (CO_2) and nitrogen, and was formed mainly in two ways

outgassing of CO_2 & hydrogen sulphide from the crust

arrival of CO_2, water (H_2O) and organic compounds on *comets*

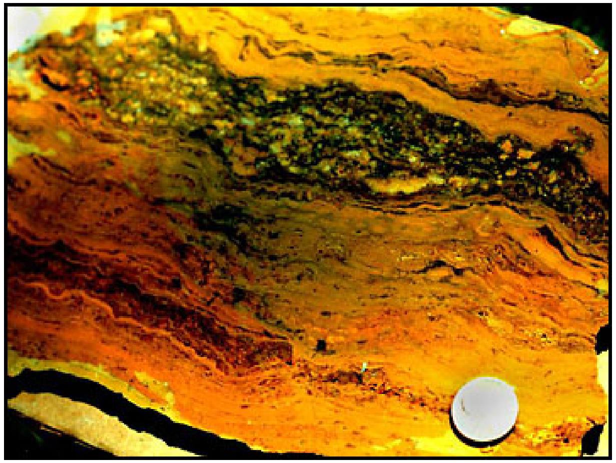
There may have been liquid water on the surface, but there is no evidence for life on Earth during the Hadean era.

The Beginnings of Life on Earth

- What is life? Hard to define in an unambiguous way, but we will use the following simple working definition:

"a material system which possesses the ability to self-replicate and evolve in response to changing environments"

- 3.5 Byr ago, soon after the dawn of the *Archean era*, we find the first firm evidence for life on Earth.



Stromatolites - layered calcium carbonate from early bacteria

- The *Archean* era followed the Hadean era, and is characterised by the oldest rocks found on Earth.

Modern-day ‘stromatolites’, Shark Bay, Australia

© UCLA

Formation of Earth's atmosphere and oceans

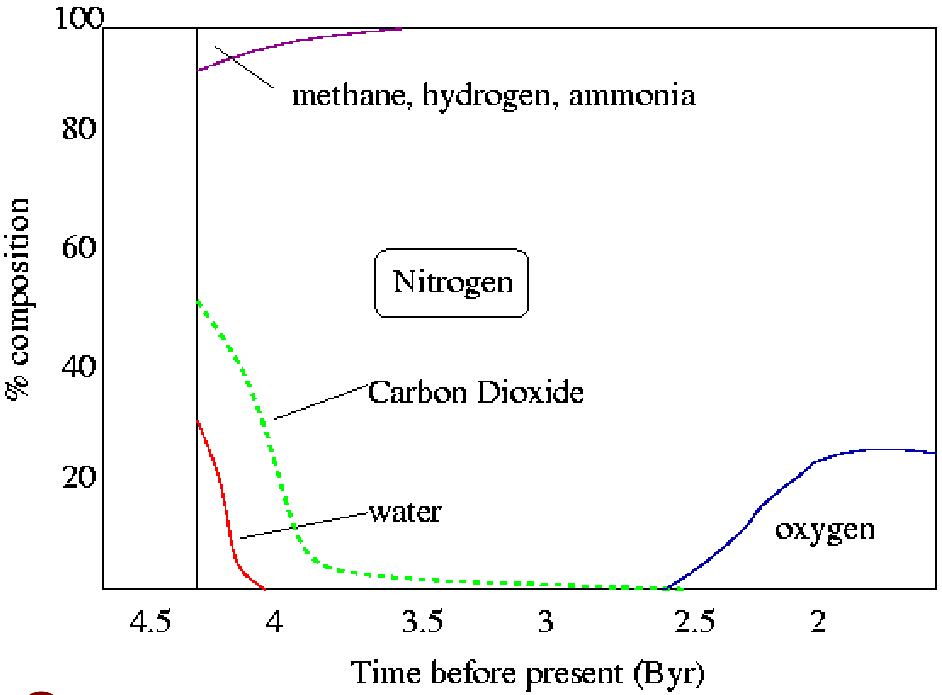
- During Hadean era, energy released by incoming planetesimals melts surface.

- Gases such as H_2O and CO_2 driven from molten rocks into the atmosphere (outgassing)

- As Earth cools, water vapour condenses and rains out into oceans.

- Some CO_2 dissolved in the rain reacts with surface minerals and is 'locked up'

3.5 – 4 Byrs ago, atmosphere has a few % CO_2 , and negligible O_2



Basic Structure of Life on Earth

- All known life forms on Earth are based on the same small set of molecules and chemical reactions

- Central among these are *proteins*

These are the active elements of cells.
- aid and control the cell chemical reactions
- receive signals from outside the cell.
- control the processes by which proteins are made from the instructions in the genes.
- form the structures that gives cells their shape
- form parts of the linkages that join cells together into tissues and organs

- The building blocks of proteins are *amino acids*

Creating amino acids

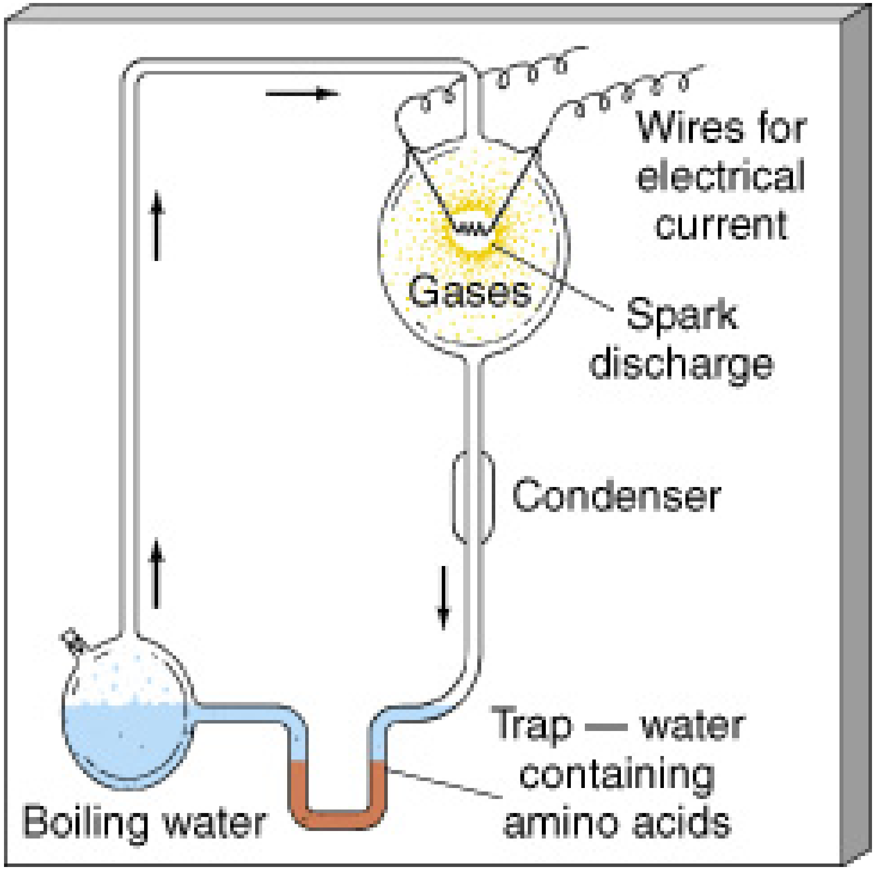
- An early experiment - the Miller-Urey experiment - was successful at creating amino acids from basic molecules

- Closed container, holding water, methane (CH_4), ammonia (NH_3) and hydrogen gas

- Electrical sparks (simulating lightning) were passed through this mixture for a few days

- Amino acids produced!

.. But only if there is insignificant carbon dioxide.



Miller-Urey experiment, 1952

- So given what we know about conditions in the early atmosphere, this means of creating amino acids was probably not dominant.

So where could they have come from - SPACE???

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- Meterorite material, such as that in the Murchison meteorite, contains up to 60 different amino acids

- Recently, researchers have shown that small molecules on an icy surface combine into amino acids when irradiated with UV

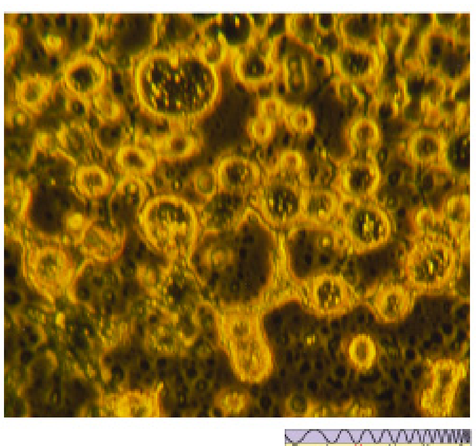
- Life on Earth based on carbon chemistry, with amino acids being basic building blocks
- Miller-Urey experiment created amino acids from basic molecules, sparked with electricity in a sealed vessel
- However, current notions about conditions on the early Earth suggest too much CO_2 for this process to work
- Amino Acids have since been discovered in space (molecular clouds, meteoritic material)
- New experiments demonstrate how amino acids could be formed on icy comets

From amino acids to life - how does chemistry become biology?

- From amino acids it is still a long way to the construction of complex, self-replicating molecules.

- *To start*: Some way is needed to keep amino acids separate from the ‘primordial soup’, to allow development of complexity

- In a *watery medium*, certain simple molecules spontaneously form membranes, separating ‘inside’ from ‘outside’



Oily globules found in meteorite material indicate that the process of formation of elementary ‘cell-like’ structure may be ubiquitous.

The Pre-Cambrian Period

- Single-celled organisms (bacteria, archaea) or aggregates of these (algae) dominated life *until about 600 million years ago*.

- About 600 million years ago, some basic multi-celled creatures found - but not many! Also, little evidence of cell specialisation or communication

- Most of life's history on Earth has been dominated by 'slime'

Layered 'mats' of stromatolites in an impression of the pre-Cambrian world.

These organisms were *photosynthesising* using CO_2 and producing oxygen.

It is believed that this process *changed the atmospheric composition*, producing enough oxygen for other life to take hold

The Cambrian Explosion

540 million years ago came the Cambrian Explosion - a huge growth in multi-cellular creatures

Basically all main groups (phyla) of life appear on the planet within the space of maybe 5-10 million years

Main evidence for this is found in the *Burgess Shale* - Cambrian rock formation found in the western Canadian Rockies

Creatures were buried in an underwater avalanche of fine mud, preserving details of the soft tissues (Only hard parts are preserved in most other Cambrian deposits - limiting information.)

What is needed for evolution of complex life?

What might be the requirements for life elsewhere in the solar system or universe?

It is obvious that our ideas will be biased towards the type of life with which we are familiar

However, there are some general principles of physics, and hence chemistry and biology, which we believe to hold true everywhere. This leads to the following likely requirements:

CARBON **WATER** **OXYGEN**

These arise from considerations of science, rather than science fiction!

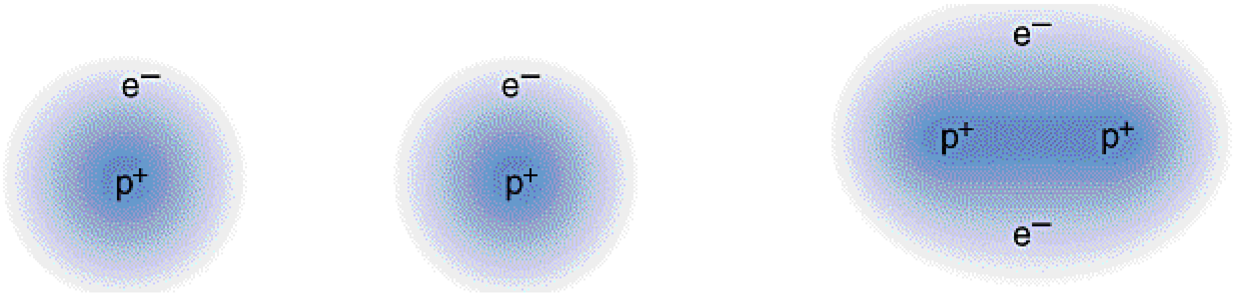
Carbon - an abundant and versatile element

↸ Quantity

The element Carbon (6 protons, 6-8 neutrons, 6 electrons) is the fourth most abundant element in the universe

↸ Strength

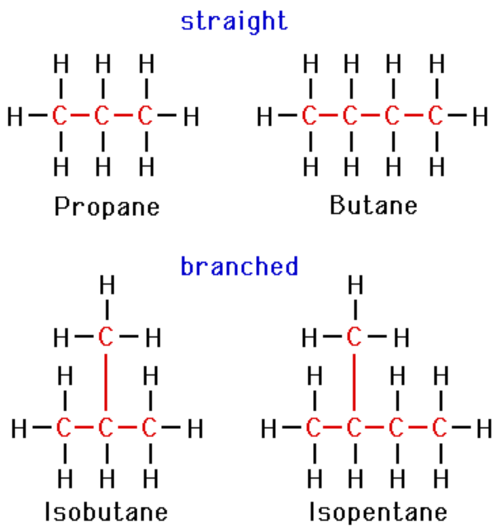
It has the greatest ability to form covalent bonds (strong chemical bonds in which electrons are shared between atoms)

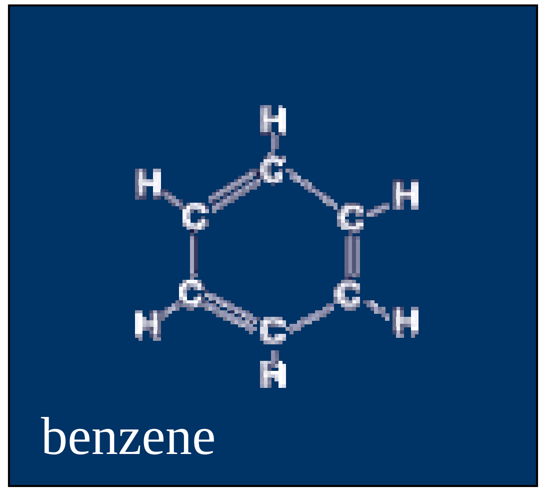


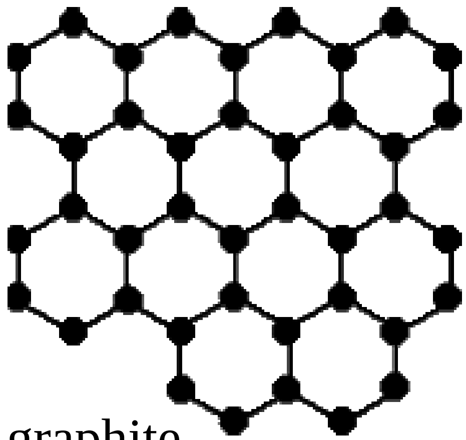
Covalent bonds are very strong. It requires a lot of energy to break a covalent bond, so carbon chemistry can withstand quite high levels of heat and radiation

Complexity and variety

Carbon has a remarkable tendency to bond with itself. It readily forms ring, chain and sheet structures.







graphite

This permits a *complex* biochemistry.

It forms a greater variety of chemical bonds than elements with similar chemical properties (e.g. silicon).

This means a greater possible *information* content in carbon chemistry

Information content

Carbon can combine with other elements in a huge variety of ways, and thus relatively small molecules can encode a lot of information.

Analogy

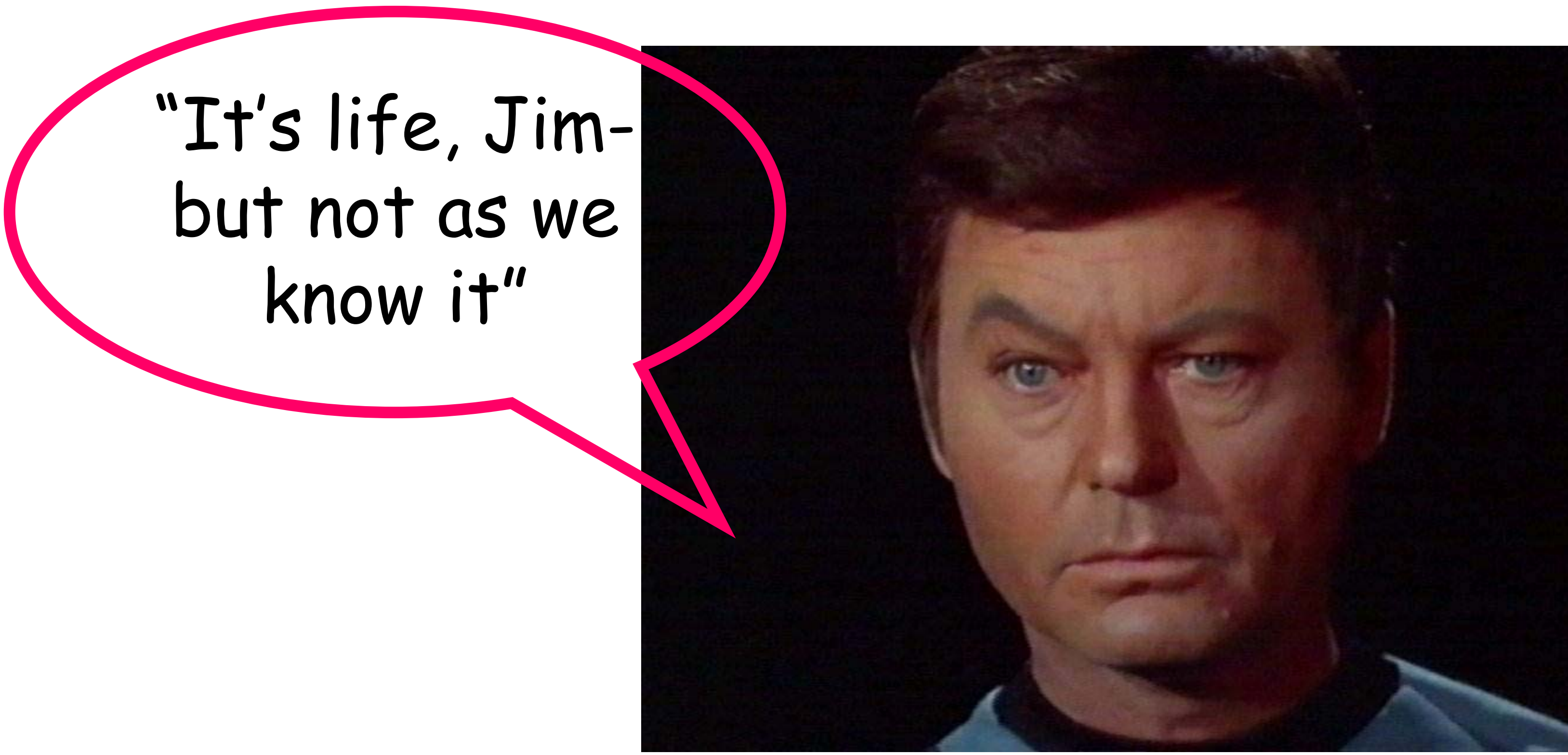
The Alphabet:

the English alphabet has 26 different letters (‘chemicals’) which can be combined (‘bonded’) in a large number of ways, storing a lot of information in a short string (‘molecule’)

Computer Binary:

Computer binary uses only ‘1’ and ‘0’ to encode information. The combinations are much more restricted, and the length of string needed to store information is much longer

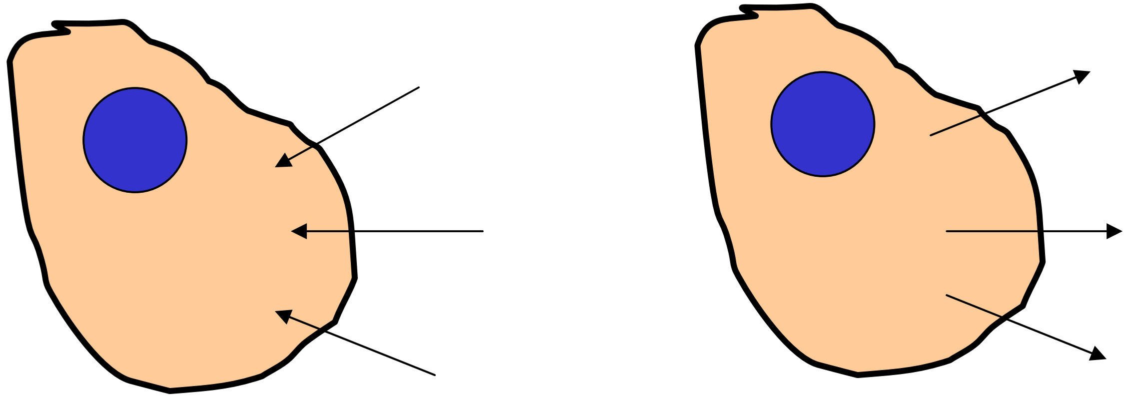
“ 01101001 01110100 00100111 01110011 00100000 01101100 01101001 01100110 01100101 00100000 01001010 01101001 01101101 00100000 01100010 01110101 01110100 00100000 01101110 01101111 01110100 00100000 01100001 01110011 00100000 01110111 01100101 00100000 01101011 01101110 01101111 01110111 00100000 01101001 01110100”



Importance of Water

Of all requirements for life, most biologists would agree that the need for liquid water (or some other liquid) is paramount

Why? transport across cell membrane



brings nutrients in   takes waste products out

Water has remarkable properties, making it a likely candidate for this vital function.

Properties of Water

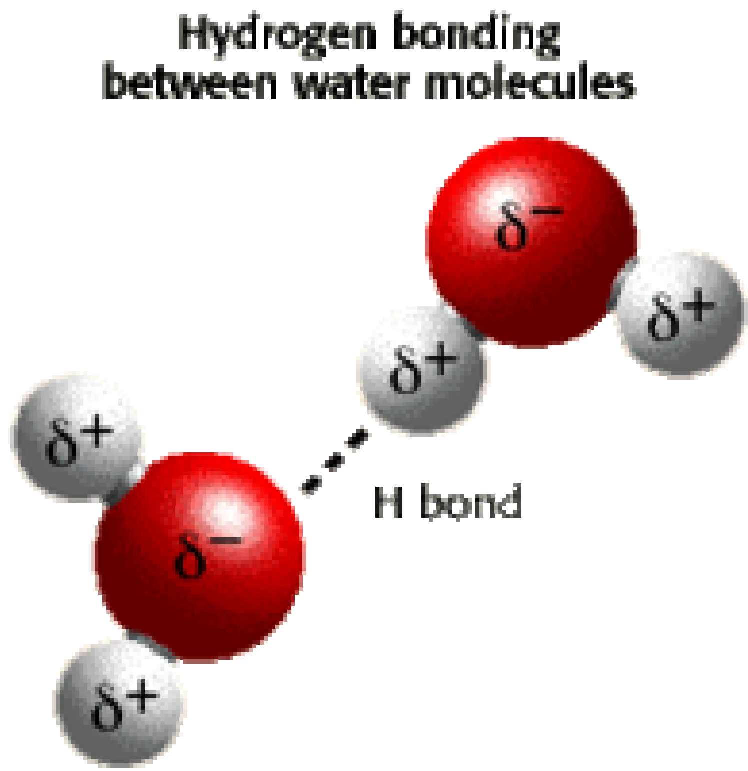
- Water, H_2O, is a compound of the most abundant element, and the third most abundant element in the universe.

- Water exists as a liquid over a large range of temperatures suitable for carbon chemistry

  In our atmosphere, this range is $0^{O}C$ to $100^{O}C$

  If atmosphere is at higher pressure, the range extends up to $363^{O}C$

- This is an unusually broad range, and is not significantly overlapped by many other abundant molecules.



Reason is the type of chemical bonds in the water molecule (polar bonds) in which the electron is unequally shared.

This also bonds water molecules to each other (as a liquid) at quite high temperatures, and makes water an excellent solvent and electrical conductor.

Oxygen

Oxygen is a highly reactive element – if it were not continually renewed by living organisms it would disappear from the present atmosphere in a few million years.

Around 2.5 billion yrs ago, there was very little atmospheric oxygen – however the oxygen produced by cyanobacteria in the oceans reacted with iron ions in the oceans.

Oxygen thus produced was ‘locked up’, until surface rock was saturated – taking about a billion years.

Banded iron formations, produced by cycles of high/low iron oxide deposition.

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Need for Oxygen

- We have already mentioned that oxygen chemistry is very active providing a ready energy source for biochemical reactions

- Biochemistry can proceed without oxygen, but does so at a much more sluggish pace (less available energy)

- e.g. Fermentation versus respiration:

(anaerobic) yeast metabolism proceeds via fermentation:

Glucose $\rightarrow$ ethyl alcohol + CO_2 + 14.6 kcal

animal metabolism proceeds via respiration

Glucose + oxygen $\rightarrow$ CO_2 + H_2O + 263 kcal

- However - because oxygen reacts so easily, it is also damaging to biological forms (hence current fad for antioxidants)

Environmental Stability

- In addition to biochemical requirements, there are environmental requirements, which might help us when trying to assess other locations in the Universe as possible sites for life.

- Protection from radiation

  High energy radiation damages molecules by breaking chemical bonds

- Moderate and stable temperatures

  For continuous presence of liquid water (or other liquid) in early stages of life

- Presence of atmospheric ‘recycling’ mechanisms

  Linked to the above - thought to be necessary for stable temperature over a long timescale.