

Earliest Geologic Records of Life

Microfossils and Chemofossils

- 3.85 Gyrs (Akilia Island, Greenland; chemofossils, not universally accepted)
- 3.4–3.5 Gyrs (North Pole and Onverwacht, Australia, the so-called Warawoona finds; bacteria-like microfossils apparently fossilized cells of filamentous organisms, not universally accepted)
- 3.2 Gyrs (Fig Tree, S. Africa)
- 2.6–2.7 Gyrs (Eastern Transvaal, S. Africa; fossilized remnants of microbial mats, identified by relative abundances of H, C, N, O and P; oldest evidence of life on land, requiring ozone layer and O₂ in atmosphere)

Isotopic evidence (chemofossils) more reliable than shape (microfossils), but still controversial

$C^{12}/C^{13} = 120$ in fossilized material, same as in present-day living matter

$C^{12}/C^{13} = 99$ in non-living matter on Earth

Corroborating evidence:

- Depleted C¹³ has been found in other 3.8 Gyr-old rocks in other locations.
- Isotopic ratios of other elements, such as Fe, N and S, are also present in ratios characteristic of living, as opposed to never-living, material.

Chemical Evolution Theory of Life's Origins

1. the synthesis and accumulation of small organic molecules, or monomers, such as amino acids and nucleotides.
 - Production of glycine (an amino acid)
$$3 \text{ HCN} + 2 \text{ H}_2\text{O} \xrightarrow{\text{energy}} \text{ C}_2\text{H}_5\text{O}_2\text{N} + \text{ CN}_2\text{H}_2.$$
 - Production of adenine (a base):
$$5 \text{ HCN} \rightarrow \text{ C}_5\text{H}_5\text{N}_5,$$
 - Production of ribose (a sugar):
$$5 \text{ H}_2\text{CO} \rightarrow \text{ C}_5\text{H}_{10}\text{O}_5.$$
2. the joining of these monomers into polymers, including proteins and nucleic acids. Bernal showed that clay-like materials could serve as sites for polymerization.
3. the concentration of these molecules into droplets, called protobionts, that had chemical characteristics different from their surroundings. This relies heavily on the formation of a semi-permeable membrane, one that allows only certain materials to flow one way or the other through it. Droplet formation requires a liquid with a large surface tension, such as water. Membrane formation naturally occurs if phospholipids are present.
4. The origin of heredity, or a means of relatively error-free reproduction. It is widely, but not universally, believed that RNA-like molecules were the first self-replicators — the RNA world hypothesis. They may have been preceded by inorganic self-replicators.

Monomer Production:

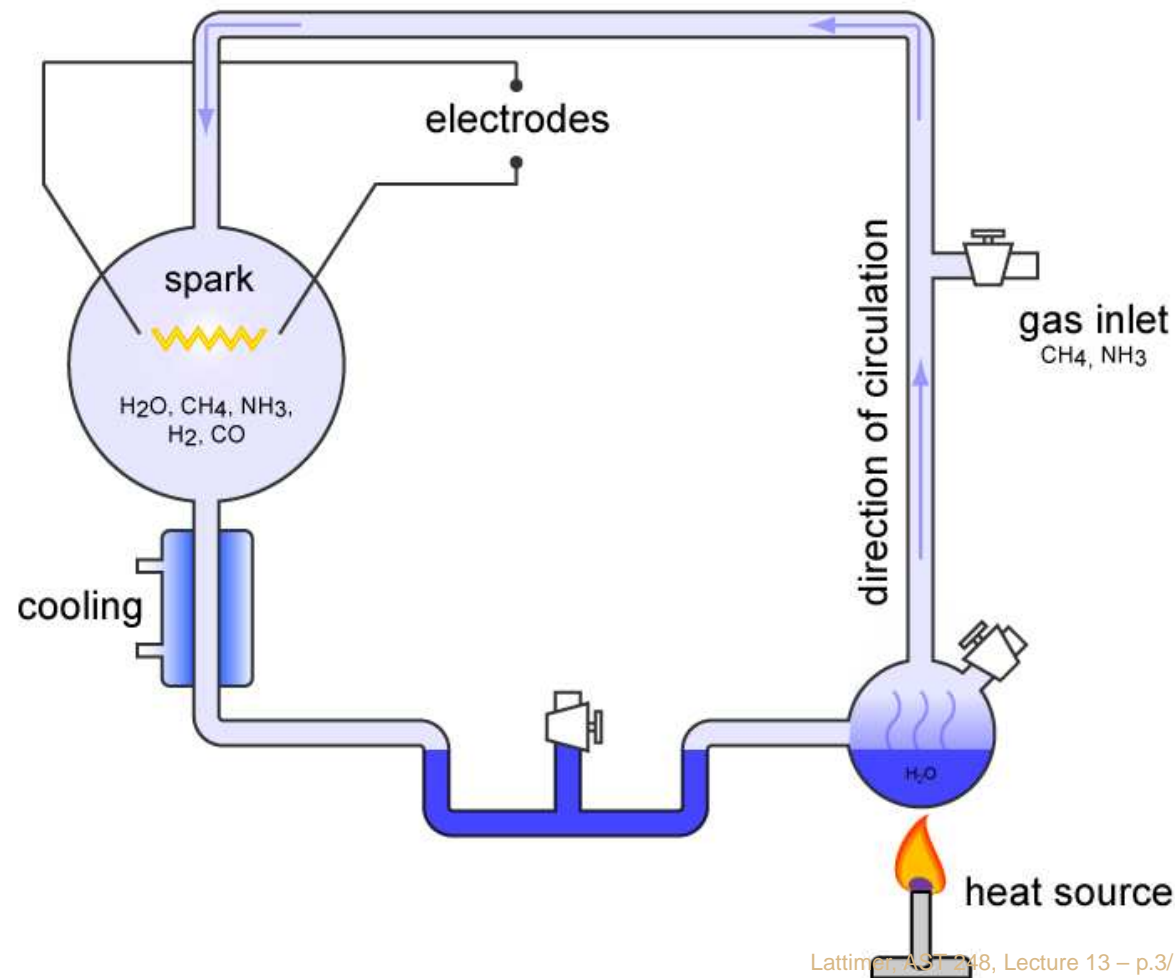
- Step 1 is possible if the early Earth's atmosphere was highly reducing as opposed to oxidizing (cf. Miller & Urey experiment).

However, models point to a less reducing atmosphere dominated by CO_2 , although other studies suggest H escaped more slowly on early Earth and its abundance wasn't negligible after all.

Nevertheless, highly reducing conditions extant near hydrothermal vents and in volcanos.

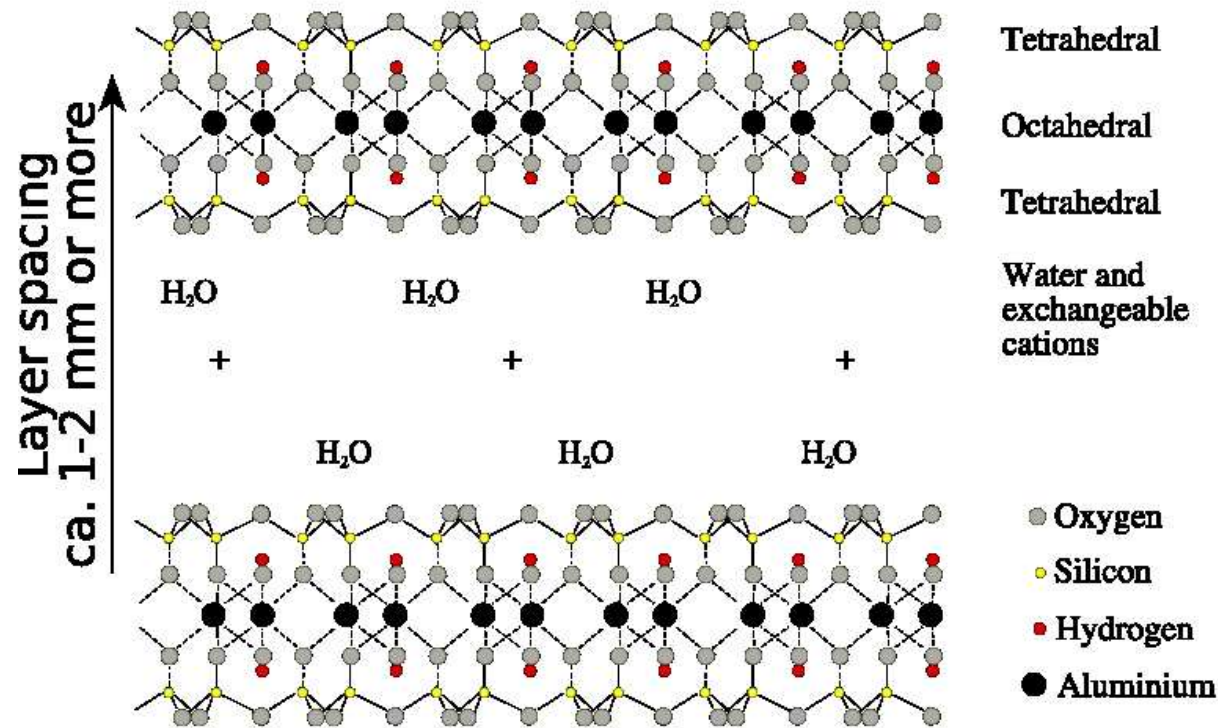
In addition, comet and asteroid impacts would have contributed much organic material and primitive compounds.

- Energy sources to drive initial chemical reactions available from UV solar radiation, radioactivity, electrical discharges (lightning), cosmic rays and solar wind (Earth's magnetic field not yet formed). Volcanic and vent energy available near hydrothermal vents.



Clays and Polymerization

- Clay structure is that of alternating negatively charged sheets of Si O_4 and Al O_4 tetrahedra separated by positive cations (Ca, Na, Fe, or Mg).
- Clays are extremely common on the Earth and Mars.
- Charged layers and cations provide multitudinous sites for monomers to stick.
- Water can easily flow through the structure as the layers are separated by 1 mm or more, enabling dehydration.
- A cubic centimeter (thumb-tip) of clay has the net surface area of a football field.
- Many peptide bonds are catalyzed by clays; RNA strands up to 100 bases in length have been produced in laboratories; lipids can be polymerized into pre-cells, sometimes containing short RNA strands.



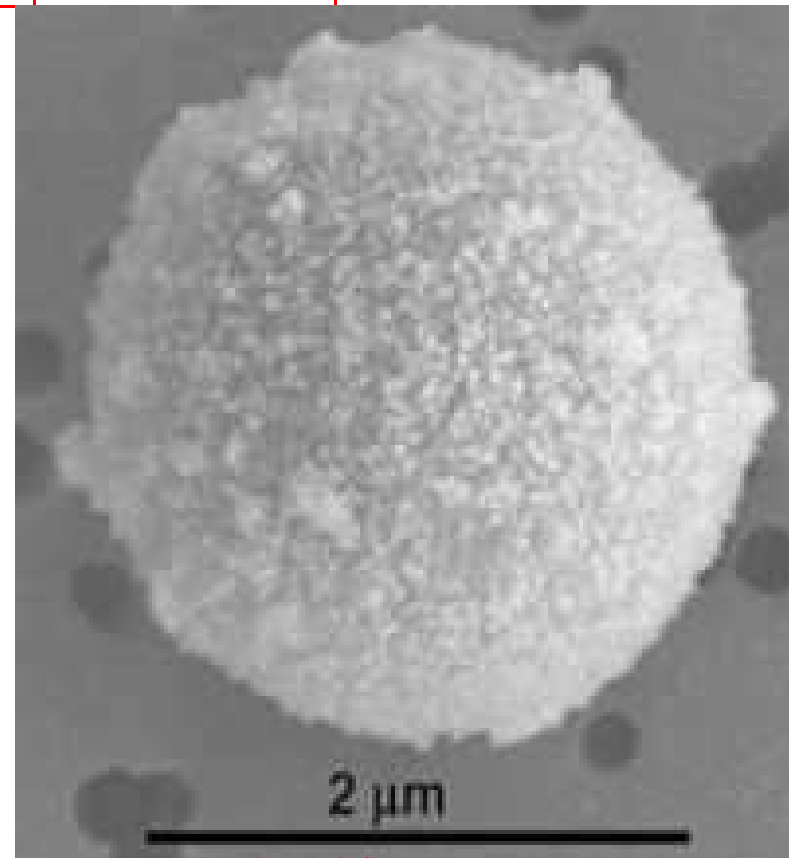
Andreas Trepte, translated by User:Itub; Wikipedia

Droplet Formation

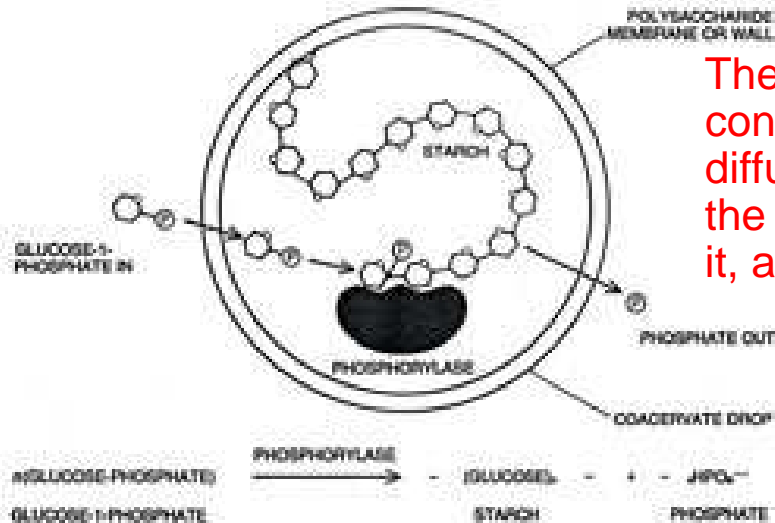
- High surface tension of water leads to large drops, not individual molecules

Properties	8 small drops	1 large drop
radius (mm)	1	2
volume per drop (mm ³)	$(4\pi/3) \cdot 1^3$	$(4\pi/3) \cdot 2^3$
total volume (mm ³)	$32\pi/3$	$32\pi/3$
surface area per drop (mm ²)	$4\pi \cdot 1^2$	$4\pi \cdot 2^2$
total surface area (mm ²)	32π	16π

- Polymeric clumps (coacervates) observed
- Phospholipids self-assemble into films forming semi-permeable membranes
- Concentration of polymers
- Existence of enzymes for growth
- Fission forms daughter drops
- Limited raw material, growth enzyme
- Random inheritance of important enzymes
- Keys: Autocatalytic polymers, systematic inheritance

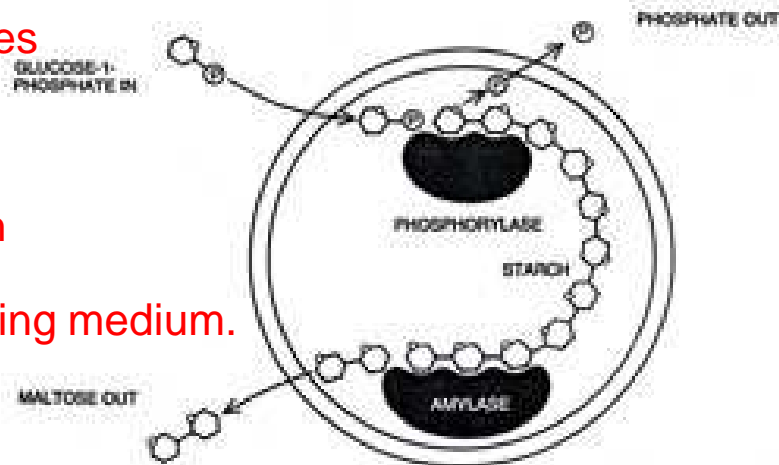


Droplet Growth



The droplet, consisting of protein and polysaccharide, contains the enzyme phosphorylase. Glucose-1-phosphate diffuses into the droplet and is polymerized to starch by the enzyme. The starch migrates to the wall, thickens it, and increases volume of droplet.

One enzyme, phosphorylase, polymerizes glucose-1-phosphate to starch. The second enzyme, amylase, degrades the starch to maltose. Droplets in this instance do not grow because the starch disappears as fast as it is made. The maltose diffuses back into surrounding medium.



RNA World

Prebiotic RNA forerunner if it could:

- replicate without proteins
- catalyze all steps of protein synthesis

RNA today does not have these properties

Proteins not first: RNA, DNA essential

Evidence for RNA world:

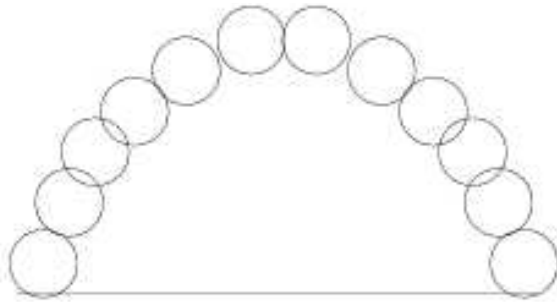
- RNA enzymes called ribozymes play a central role in protein synthesis.
- RNA is also an important catalyst for the synthesis of new RNA.
- RNA in ribosomes, not protein, catalyzes protein formation.
- Ribozyme-catalyzed reactions are slow, but are sped up a thousand-fold by accompanying proteins.
- Primitive RNA sequences can evolve under abiotic conditions.
- Unlike double-stranded DNA, single-stranded RNA can take a variety of shapes specified by their nucleotide sequences.
- RNA thus have both a genotype (sequence) and phenotype (shape) that interacts with surrounding molecules.
- Protein transcription in Archaea and Bacteria have different forms implying they independently formed DNA genomes and methods of transcribing DNA into RNA.

What would happen:

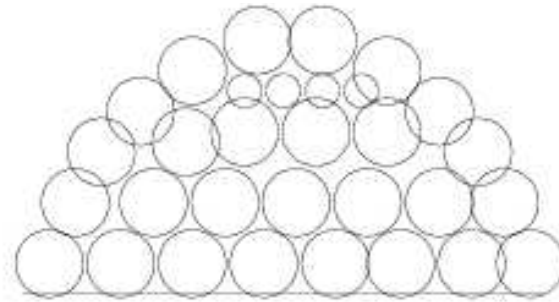
- Reactive nucleotides made random polymers, and the first RNA molecules could have been short, virus-like sequences.
- Inside protobionts, some amino acid polymers could have had rudimentary catalytic properties, aiding in RNA replication.
- Under certain conditions, some RNA sequences are more stable and replicate faster and with fewer errors than other sequences.
- RNA-directed protein synthesis may have begun as a weak binding of specific amino acids to bases along RNA molecules which served as templates holding a few amino acids together long enough for them to link (rRNA does this today).
- Some RNA molecules may have produced short amino acid chains that were enzymes for RNA replication.
- Other RNA sequences may have enabled the use of high-energy molecules like H_2S to provide energy.
- A protobiont with self-replicating, catalytic RNA would dominate the population of molecules.
- The first protobiont would have only limited genetic information, but because their properties were heritable, they could be acted on by natural selection.
- Mutation (occasional copying errors) and natural selection leads to more stable and faster replicating varieties.
- Natural refinement to replace RNA by DNA as the repository of genetic information; being double-stranded it is more stable and accurately reproduced.

Genetic Takeover Hypothesis

- RNA, nucleotides too complex, evolved from simpler systems
- Interdependency evolved by means of scaffolding

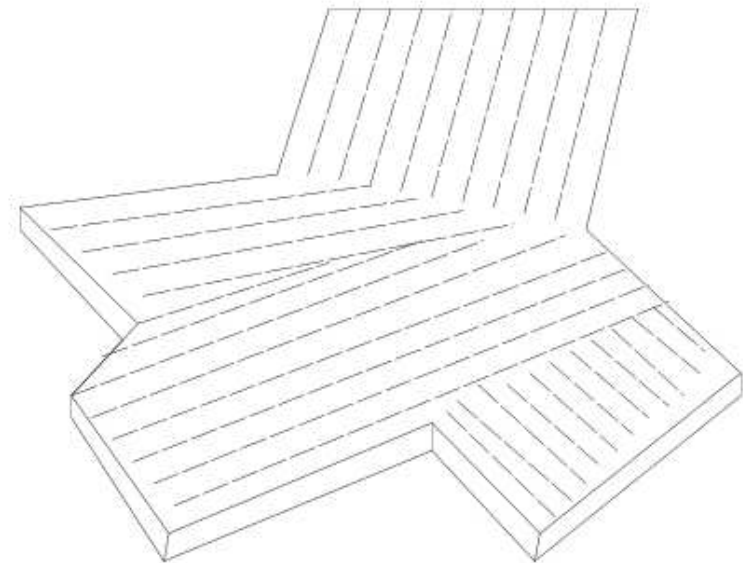


stone arch



stone mound

- First organism contained information only; material and machinery for replication provided by environment
- Organic molecules too varied, reversible bonds too weak, to be simple and self-assembling
- Simple inorganic self-assemblers with strong reversible bonds exist: soap bubbles, clay crystals
- Growth naturally controlled by supersaturation
- Life is information: crystal defects



- Information: control of environment (supersaturation, raw materials?)
- Evolution (natural selection) by direct genetic action
- Advantage gained by going to indirect genetic action
- Organic polymers have advantage of efficiency, flexibility, size
- Possible links:
 - Photosynthesis can control supersaturation
 - Amino acids control concentration of metal ions (Al, Mg)
 - Polysaccharides control consistency of solutions
- Gradually, structure & genetic information transferred to organic polymers
- Organic polymers take over. Efficiency and self-assembly work against inorganics

Panspermia or Exogenesis

- Once an outlandish idea, presence of organic material in meteorites and comets implies organic material forms and survives in harsh interplanetary space.
- Discovery of endospores, which might remain dormant for hundreds of millions of years, points to possible long-term survivability.
- Rocks can be ejected into space as a result of an impact's explosion.
- Earth, Moon, Mars and Venus have been exchanging material for billions of years. Over 3 dozen known meteorites believed to have originated on Mars; even more believed to have originated on the Moon.
- Original blast, fiery passage through atmosphere, and exposure to solar wind and cosmic rays in between melts or destroys a relatively thin layer on a meteorite; sensitive, volatile material within is protected.
- Vast majority of projectiles from Venus or Mars will orbit millions of years before landing again on a planet, but 1/10,000 of them will land within a decade.
- Migration from other stellar systems is extremely unlikely, both in terms of number of such meteorites (no known extra-solar meteorites) and in terms of travel times.
- If life is extremely difficult to form, then perhaps it got here by migration. But this just moves the problem of origin to another place. Furthermore, no other location known where formation might have been easier.
- If life is easy to form, the origin of life in the solar system would take place where suitable conditions arose first, and migrate from there.
- If it is possible for Earth life to survive on another planet like Venus or Mars, then it might well be there already because of migration. This means if life is discovered on Mars we have to carefully consider whether it is indigenous or not.

Circumstantial Evidence for Panspermia[†]

- A relatively narrow time window exists for geogenesis, between LBH 3.9 Gyr ago and the earliest evidence for life on the Earth, 3.5-3.85 Gyr ago. On the other hand, the age of the Universe is about 13.7 Gyr, and abundant C, N and O have been present for 12.7 Gyr. This window for exogenesis is thus about 9 Gyr.
- Existence of extremophiles and ability for dormancy up to millions of years.
- Many potential habitats for life exist outside of Earth within our Solar System (Mars, Europa, Enceladus, Triton, Titan) and, by inference, outside our Solar System.
- Exchange of material within inner Solar System well-documented.
- Disputed evidence for extraterrestrial life, including
 - Red Rain of Kerala: Analyses (2003-6) of dust yielded spores claimed to be extraterrestrial, which “reproduce plentifully” even in “water up to 300°C”.
 - Meteorite ALH84001 from Mars was shown (1996) to contain microscopic structures resembling terrestrial microfossils, but thought by many to be too small to sustain life. Furthermore, abiotic origin is very possible. Recent research into nanobes makes this find interesting again.
 - Several studies (2000-2003) claim to obtain microorganisms from high altitudes (up to 40 km) that are common terrestrial organisms: not inconsistent with panspermia.
 - Claims of bacteria inside meteorites (2001) with non-terrestrial DNA.
 - Lingering suspicions by some Viking lander researchers that positive results in the life experiments were not false-positives.

Counterevidence Against Panspermia

- Space is a damaging environment (cosmic rays, extreme cold).
- Studies of ice core bacteria indicate a half-life for dormant DNA of 1.1 million years in a radiation-free environment.
- Occam's Razor says when developing an hypothesis, avoid making unsupported assumptions. On this basis, geogenesis is supported as the simpler hypothesis: life originates as a matter of probability as opposed to being a singular event, or Earth does not meet proper conditions.

Directed Panspermia

- Crick and Orgel proposed life is deliberately spread throughout universe by intelligent civilizations. Cost-effective strategy for seeding life is to randomly send small grains containing DNA. Motivation: avoid catastrophic annihilation or to terraform planets for later colonization. Crick later removed his support in favor of the RNA world hypothesis for life's origin.
- Abundant science fiction rationalizations, including the explanation for the improbable tendency for fictional extraterrestrials to be humanoid and living on similar (*i.e.*, class M) planets (a result of genetic codes spread through the Universe by the "Ancient humanoids").