Introduction to Astrobiology

Chapter 3
Origin of life

Origin of life:
the scientific approach

- The origin of terrestrial life is one of the fundamental topics in astrobiology

- Abiogenesis
  - In the scientific approach, the origin of life is treated as a sequence of spontaneous processes, called *abiogenesis*, that leads to the formation of the first living organisms starting from non biological chemical compounds

Origin of terrestrial life:
“in situ” hypothesis

- We can set contraints on the chronology and the physical/chemical conditions of abiogenesis, assuming that terrestrial life originated on Earth
  - Strictly speaking, this assumption is only a working hypothesis
  - This hypothesis is adopted, more or less explicitely, by most authors
  - According to some authors, the life that we know originated outside Earth and was somehow transported to Earth
    - There are no experimental evidences in support of this hypothesis
      - Although we do have evidence of complex organic material produced in space and delivered on Earth
    - The hypothesis of an external origin has some disadvantages:
      - We need to invoke the possibility of transportation of life
      - We shift the problem of the origin of life to some unknown location and time, for which we do not know the physical/chemical conditions

Chronology of the origin of terrestrial life

- We can set temporal limits on the epoch of life formation by comparing the chronologies of:
  - the processes of Earth formation and early evolution
    - the age of Earth’s formation and early evolution sets an upper limit on the age of the origin of life
  - the oldest evidence of life found in the terrestrial crus
    - the age of the oldest traces of life set a lower limit on the age of the origin of life

- By comparing these time-scales, assuming that life originated on Earth, we can estimate the epoch of life formation and the time interval available for life formation

Dating techniques

- Radiodating
  - Radiodating techniques play a fundamental role in these type of studies
  - Thanks to radiodating we can date with precision the age of the Solar System and Earth's formation, but also the age of the oldest terrestrial rocks bearing signatures of past life
  - In practice, one compare the abundances of radioisotopes with different decay times, with abundances of stable isotopes
  - For dating events in the remote past, close to the Earth's formation, we need radioisotopes with very long life times
  - Examples:

    ^{238}U (τ=4.5x10^9 anni), ^{235}U (τ=7.0x10^8 anni)

Age of formation of the Solar System

- The age of formation of the Solar System can be dated with accuracy from the analyis of meteorites
- Date of the oldest objects in the Solar System:

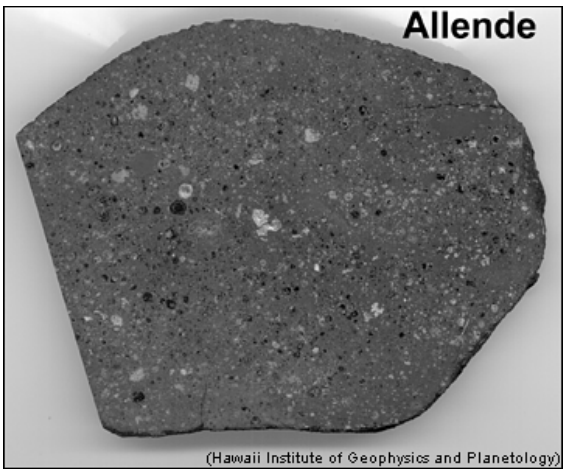
  4.57 x 10^9 yr

  - Example: Allende meteorite

    a type of chondritic meteorite

    classified as CV

    Felt in Mexico in 1969



Age of formation of the Earth-Moon system

- From radiodating of Earth and Moon rocks
  - Moon formation: ~ 4.50 x 10^9 yr
  - Oldest terrestrial rocks: ~ 4.45 x 10^9 yr

- The scenario of Moon formation
  - Impact of the proto-Earth with a planetary embryo
  - Formation of a cloud of debris around the Earth
  - Condensation of the Moon from the debris
  - Theoretical models suggest that the Moon would have formed at a distance of a few Earth's radii

The oldest terrestrial rocks

- It is extremely difficult to find terrestrial rocks with ages close to the epoch of Earth formation and early evolution
  - This makes very hard dating the origin of life
- The main reason for this difficulty is tectonic activity, which is constantly recycling the Earth's crust

- No traces of Earth's crust are available for the first 500 millon years of Earth's history
  - Initially, because of the complete fusion of the crust generated by the Moon-forming impact
  - Intense meteoritic bombardment may also have contributed to crust melting

The oldest terrestrial rocks

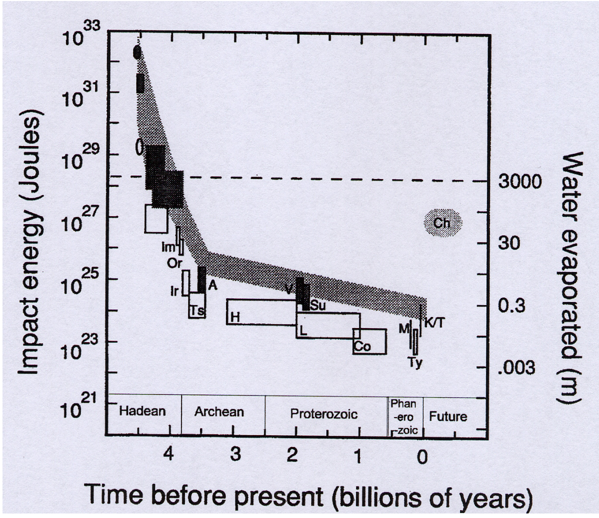
- The oldest, well preserved crust material has ages of about 3.2 – 3.5 10^9 Ga
- Older material exists, with ages of 3.5-4.0 Ga, but is sparse and quite altered
  - Notwithstanding, zircon minerals with ages up to 4.4 Ga have been found, incorporated in "younger" strata
- Oldest geological strata found in some locations in Australia, Greenland and few other places on Earth

The oldest evidence of water on Earth

- The analysis of the oldest zircons indicate that liquid water was already present on Earth 4.4 Ga
- How diffuse was water at that epoch we do not know

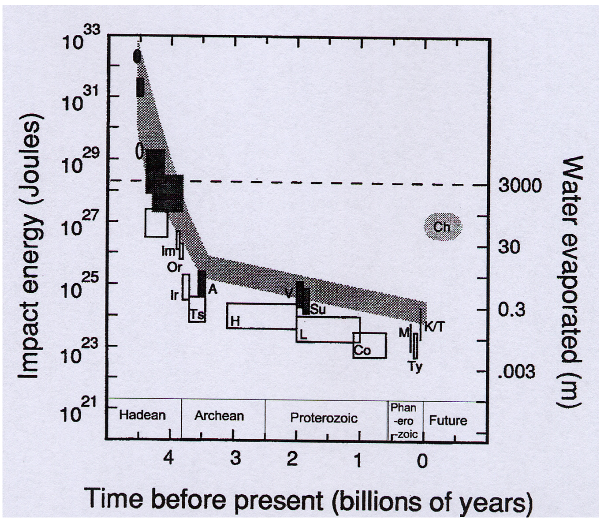
The "Late heavy bombardment" (LHB)

- The analysis of impact craters on the surfaces of the bodies of the inner Solar System indicates a <u>long history of impacts</u>, starting from the epoch of Solar System formation
- The analysis of <u>Moon</u> impact craters indicates the existence of an episode with a large number of heavy impacts that took place well after the formation of the Solar System
  - This "<u>late heavy bombardment</u>" must have taken place also on Earth, even if we do not have direct geological evidences
  - The frequency and intensity of the impacts drastically decays between 4.1 e 3.7 x 10^9 Ga
  - Evidence for the existence of the LHB start to accumulate also from other bodies of the Solar System



Implications of the "Late heavy bombardment" (LHB)

- Models of planetary system formation
  - Not easy to understand why a strong dynamical instability would have taken place after ~600 millon years after the origin of the planetary system
- Origin of water and organics on Earth
  - The LHB may have significantly contributed to delivery water and organic material on Earth
- Origin of life
  - The cumulative effect of the impact may have made impossible for life to appear until the end of the LHB



Testing the origin of Earth's water

- The possibility that water has been delivered on Earth by impacts of minor bodies (asteroids and comets) is tested with studies of the isotopic ratio D/H
- The oceanic D/H ratio is compared with measurements performed in meteorites and comets
- So far, asteroids appear to be favoured, but the experimental evidence may change with future studies of comets

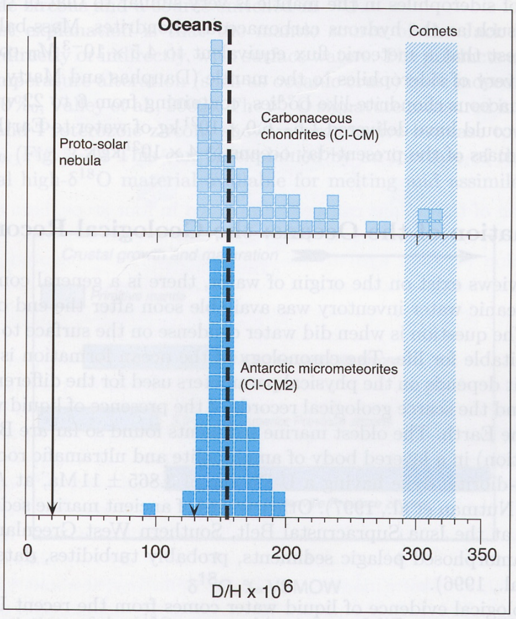


Fig. 3.2. Frequency distribution of the D/H ratios measured in carbonaceous chondrites and Antarctic micrometeorites compared to values for the PSN, Earth oceans and comets. Data: Déloule et al., 1991; Engrand et al., 1999; Maurette et al., 2000; Robert et al. 2000

Searching for the oldest traces of life on Earth

- Different types of experimental techniques are used to search for traces of ancient life in the oldest terrestrial rocks
  - Study of isotopic ratios that can be altered biologically

    Example: $^{12}C/^{13}C$
  - Morphological evidences of microscopic forms of life

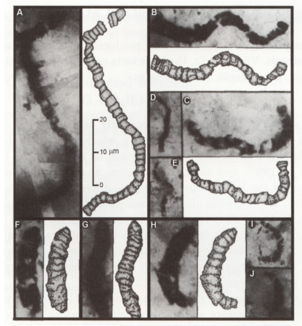
    Microfossils can be preserved thanks to the mineralization of organic matter of biological origin
  - Geological layers of biological origin

    Examples: sedimentary layers similar to presen-day "stromatolites"
- These methods only offer indirect evidences
  - Results should be taken with caution
  - However, convincing evidence can be obtained by the combination of different methods

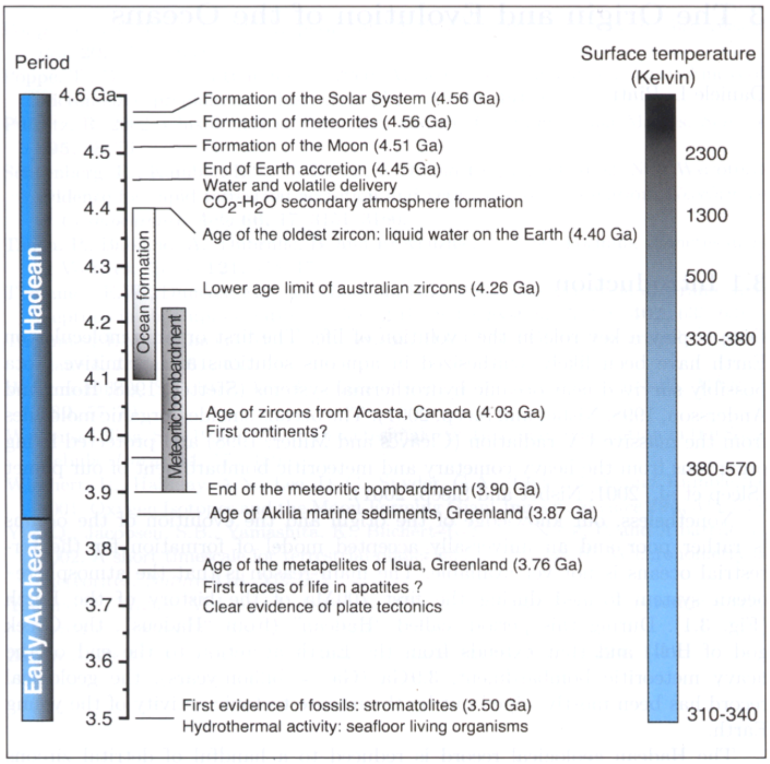
Oldest evidence of life on Earth

- The oldest, <u>tentative</u>, evidence are dated at about 3.8 Ga
  - –Sedimentary rocks in the south-east of Greenland (Isua, Akilia)
    - Based on the isotopic ratio $^{12}C/^{13}C$

- The oldest, <u>more convincing</u>, evidence are dated at about 3.2 - 3.5 Ga
  - –"Greenstone belts" in Australia (Pilbara) and South-Africa (Barbeton)
    - - Isotopic ratios
    - - Microfossils
    - - Sedimentary layers suggesting the presence of <u>diffuse life</u> in shallow water, close to the litoral



Summary of chronology relevant for studies of the origin of life on Earth



Conclusions: temporal constraints on the origin of life on Earth

- If we consider the temporal window between the end of the LHB and the oldest, tentative evidence of life, the origin of life should have taken place around 3.8 - 3.9 Ga, on a relatively short time scale (~10^6 yr)
- If we take the more robust evidence for the oldest trace of life, the origin of life should have taken place between 3.5 and 3.9 Ga, on a time scale of a few hundred millon years
  - Even if we consider the more robust evidences, life must have originated <u>before it was diffuse</u>
- These time scales can be relaxed by a few hundred millon years if we assume that life originated before the end of the LHB
  - Some authors claim that the LHB may not have been fatal for life

Properties of the Earth at the epoch of the origin of life

- The physico/chemical conditions of the early Earth set the reference frame for casting light on the prebiotic processes that should have lead to the origin of life
- We briefly mention two aspects of the physico/chemical conditions relevant to the problem of the origin of life:
  - Early atmospheric composition of the Earth
  - Early climate of the Earth

The early atmosphere of the Earth

- The primary atmosphere of the Earth must have been lost
  - This is deduced from the low abundances of rare gases (^{20}Ne, ^{36}Ar, ^{84}Kr) in the present-day atmosphere, compared to the cosmic abundances of the same elements
- Different hypothesis have been advanced on the composition of the secondary atmosphere of the primitive Earth
  - Old models

    Slow formation of the Earth, with interior cold and rich of volatiles

    Volatiles from the interior are gradually heated and released to the atmosphere

    These volcanic emissions produce a "reducing" atmosphere (rich of hydrogen), with a high content of H_2, CH_4, and NH_3
  - Present models

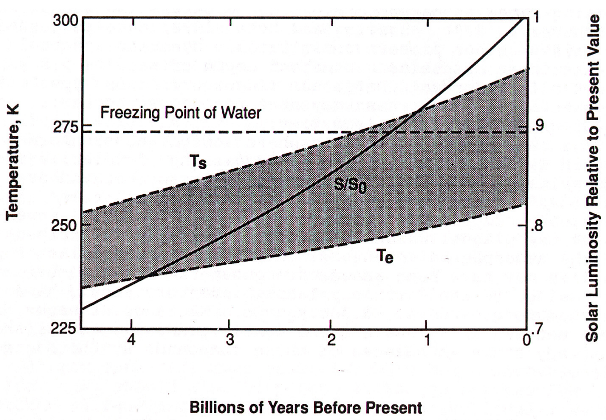
    Fast formation of the Earth (10-100 millon years)

    Because of the impacts with accreting planetesimals, the interior is hot and does not have volatiles

    By the end of the accretion process, the atmosphere is "weakly reducing", being dominated by CO_2 e N_2 with traces of CO and H_2

The early climate of the Earth: the "Faint Young Sun paradox"

- The standard model of evolution of the Sun indicates that the solar luminosity was about 25% fainter than today at the epoch of the origin of life
- With such lower level of luminosity, models of Earth climate indicate that the Earth should have been completely frozen
  - Assuming a similar intensity of the greenhouse effect as the present-day one
- We know that this was not the case, since there are evidences of liquid water at the same epoch of Earth's history
- This contradiction is known as the "faint young Sun paradox"



Te – Effective temperature of the Earth
Ts – Mean surface temperature of the Earth
The shaded region indicates the greenhouse effect

The early climate of the Earth:
the “Faint Young Sun paradox”

- Possible solutions to the paradox
  - Larger efficiency of the greenhouse effect (this is the most accepted explanation)

    Atmosphere rich in CO_2 and/or CH_4
  - Larger efficiency of internal heating ?
  - Larger value of atmospheric pressure ?

    Tested with climate models

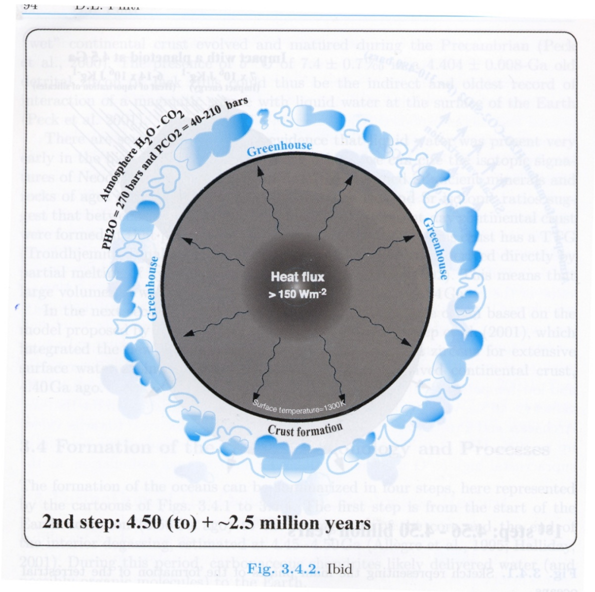
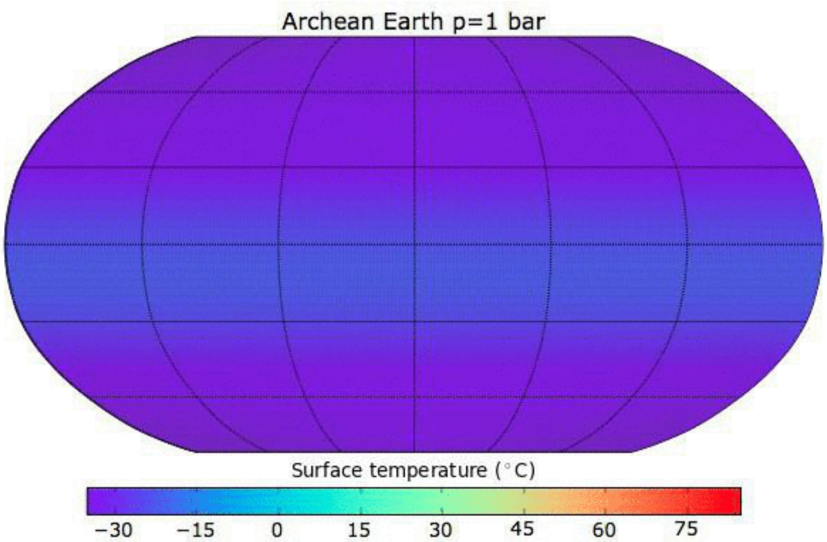
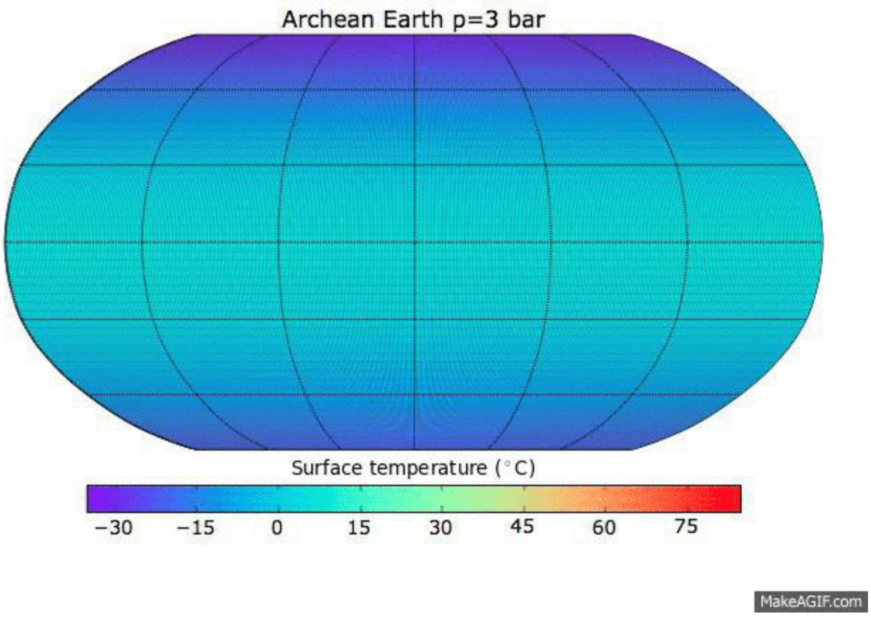


Fig. 3.4.2. Ibid

Climate simulation of the Earth in the Archean (3.9 Ga)
Present-day atmospheric composition, $p = 1$ bar



Climate simulation of the Earth in the Archean (3.9 Ga)
Present-day atmospheric composition, $p = 3$ bar



Having set the context
(time scales and physical/chemical conditions),
we now briefly summarize the
studies on the origin of terrestrial life

Studies on the origin of life

- We mention some of the fields of research related to the studies of the origin of life
  - Synthesis of biological precursors (prebiotic chemistry)
  - Emergence of metabolic and replicative functions
  - Characterization of the first living organisms

- Two types of approaches are used:
  - "bottom-up"

    trying to reconstruct complex, biological molecules in laboratory, starting from non biological constituents
  - "top-down"

    trying to cast light on the characteristics of the least evolved forms of life, proceeding "backwards" in evolution

Synthesis of biological precursors (prebiotic molecules)

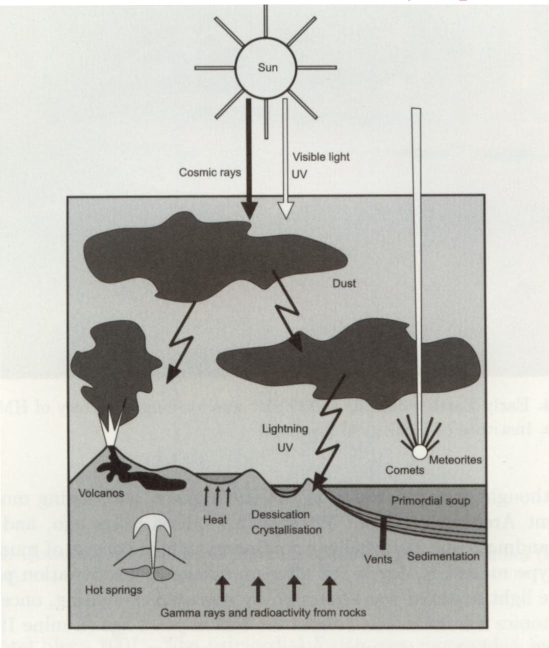
- Study of the stages of chemical evolution that precede the origin of life

- Search for the potential pathways of spontaneous synthesis of prebiotic molecules (e.g. aminoacids) useful for the subsequent synthesis of the biological macromolecules that we know (e.g. proteins)
  - One of the goals is to understand which organic molecules are the most likely to initiate these chemical pathways

- Two possible scenarios for the synthesis of prebiotic material are considered:
  - On Earth
  - In Space

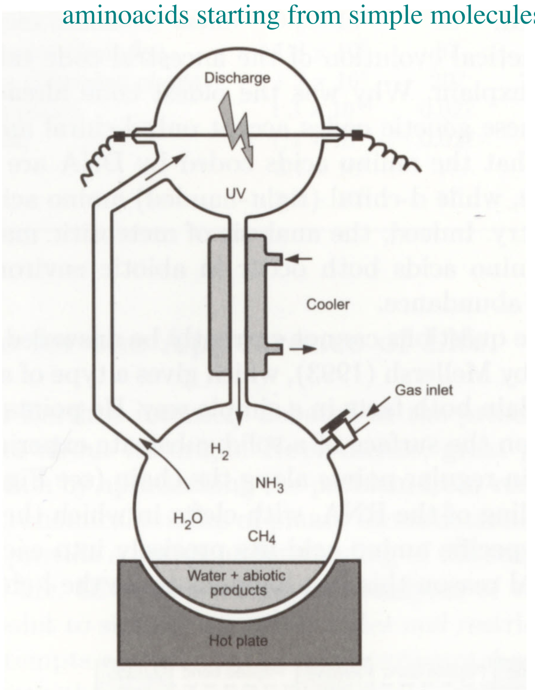
Synthesis of prebiotic material on Earth

- The physical/chemical conditions of the early Earth are simulated in laboratory experiments



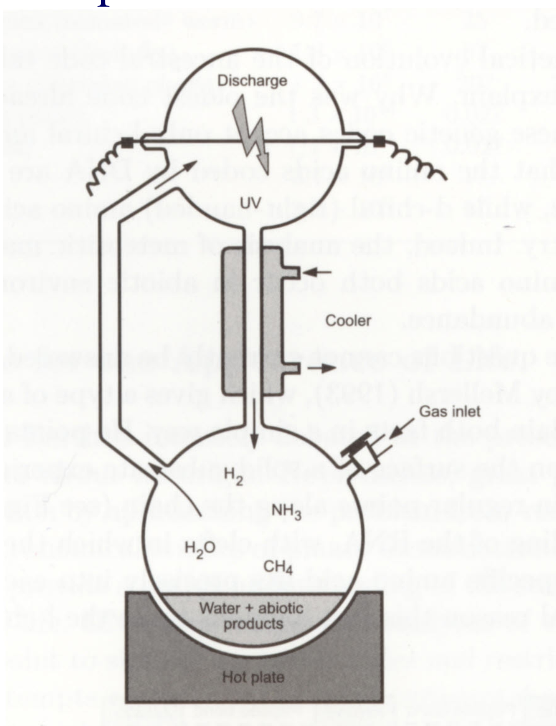
➢ The Urey-Miller experiment

In 1954, proved the possibility to form aminoacids starting from simple molecules



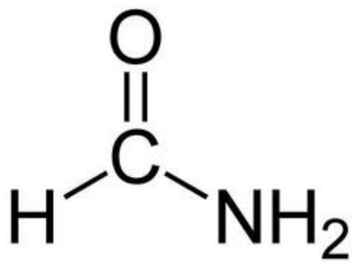
The Urey-Miller experiment

- In the original version, the authors adopted a "reducing" atmosphere, because at that time that was considered to be representative of the early Earth's atmosphere
  - The adoption of a "reducing" atmosphere gives a high yield of aminoacids
- Recent versions of the experiment adopt a "weakly reducing" atmosphere, in agreement with the current expectations for the early Earth's atmosphere
  - The experiment is still able to produce aminoacids, albeit with a much lower efficiency



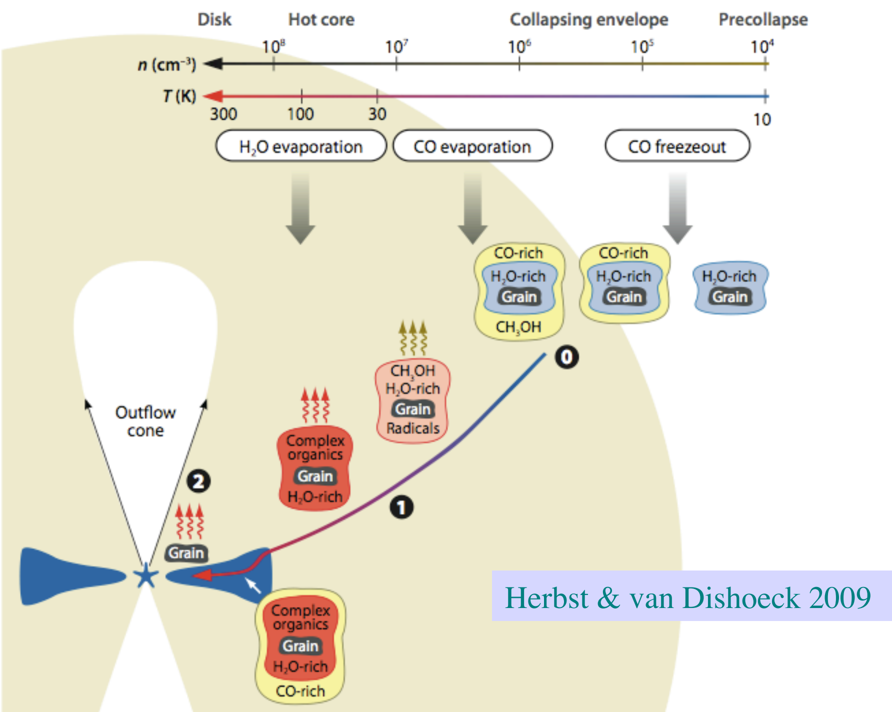
Present-day prebiotic chemistry

- A very large number of chemical pathways are currently tested in laboratory
- Some of these pathways are able to reproduce not only aminoacids, but also the nucleobasis of nucleic acids
  - As an example, a very large number of pathways can be obtained, under a large variety of conditions starting from a simple molecule, such as the formamide



Synthesis of prebiotic material in space

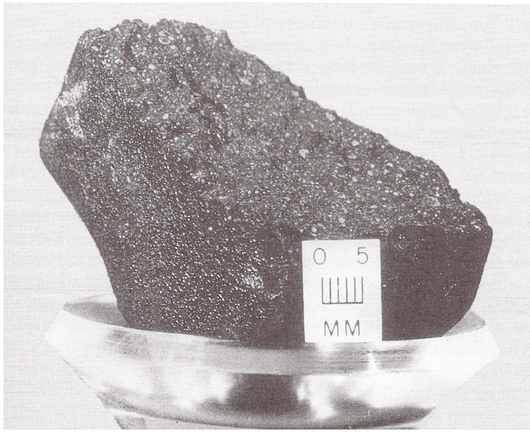
From molecular clouds to planetary formation



Herbst & van Dishoeck 2009

Prebiotic material delivered on Earth by meteorites

- Meteorites are representative of the epoch of planetary formation
  - Some of the meteorites collected on Earth show evidence of relatively complex organic material
- One of the most interesting cases is the Murchison meteorite (Australia, 1969) where evidence have been found of aminoacids and nucleobasis
  - The non-terrestrial origin of these organics compounds is confirmed by several tests:
    - Out of the 74 aminoacids found, only 11 are protein aminoacids
    - The aminoacids appear in a near racemic mixtures (both L- and D- types), at variance with protein aminoacids
  - A slight eccess of the L enantiomer has been found, consistent with the biological aminoacids

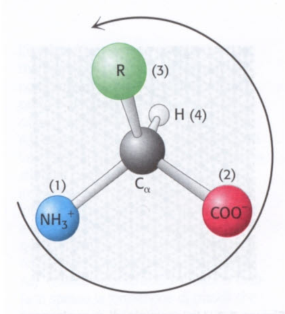


- The Murchison meteorite, together with other meteorites, proves that complex organic material may have been synthesized in space and delivered on Earth
- Important steps of prebiotic chemistry may have taken place both in space and on Earth
- Both scenarios are taken in considerations in this type of studies

Origin of the homochirality of biological macromolecules

- Understaning the <u>origin of homochirality</u> may cast light on the early stages of prebiotic chemistry

- The general idea is that a slight enantiomeric eccess was produced by some prebiotic process
  - At a later stage, the enantiomeric eccess would have been amplified up to the point of attaining homochirality



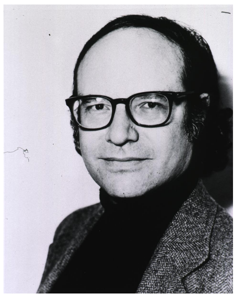
The hypothesis of an interstellar origin of a prebiotic enantiomeric eccess

- The hypothesis of an enantiomeric eccess of astronomical origin is taken into consideration
  - Motivated by the discovery of the weak enantiomeric eccesses in the Murchison meteorite
- General idea:
  - Circularly polarized interstellar radiation field would have affected the early prebiotic chemical reactions in interstellar space, leading to a small excess of molecules with one type of symmetry
- Laboratory tests are being perfomed using circularly polarized light produced in synchrotron experiments

Origin of replication and metabolic properties

- Conceptual “chicken-egg” problem
  - In present-day cells, nucleic acids and proteins are responsible for replication and metabolic functions, respectively
  - The origin of each one of these two types of macromolecules is based on the previous existence of the other one
    - The synthesis of nucleic acids is catalyzed by proteins
    - The synthesis of proteins requires the instructions stored in the nucleic acids
- Who came first?
  - Proteins or nucleic acids ?
  - Replication/genetic or metabolic functions ?
- Different approaches have been adopted to tackle this problem
  - In the past: “Metabolism first” or “genes first”
  - Presently: we search for macromolecules that show both properties

The “RNA world”



- Present-day, main stream theory in the context of origin of life studies
- Introduced by Walter Gilbert (1986) after the discovery of ribozymes
  - RNA molecules with catalitic properties
- According to this theory, the genetic system is the first to emerge, but with self-catalitic properties
  - Present-day ribozymes would be a sort of molecular fossiles of an ancient “RNA world”
- Present-day DNA-world would have emerged at a later stage because of its advantages
  - greater genetic stability
    - DNA is more stable than RNA
  - greater flexibility
    - due to the introduction of proteins specialized in a large variety of metabolic functions

The kinetic power of self replication

- In chemistry, kinetics is related to the rate of chemical reactions
- Example of comparison between normal and self-catalytic reactions
  - start with 1 molecule of catalyst X
  - assume reaction rate 1μs in both cases
- Time required to build up a mole of products (6 x 10^{23})
  - Normal case: 20 billon years
  - Self-catalytic case: 79 μs
- The kinetic control of chemical reactions could be the key for understanding the origin of life
  - see literature by Addy Pross

A, B: reactants

X: catalyst

$$A + B \xrightarrow{X} C$$

$$A + B \xrightarrow{X} X$$

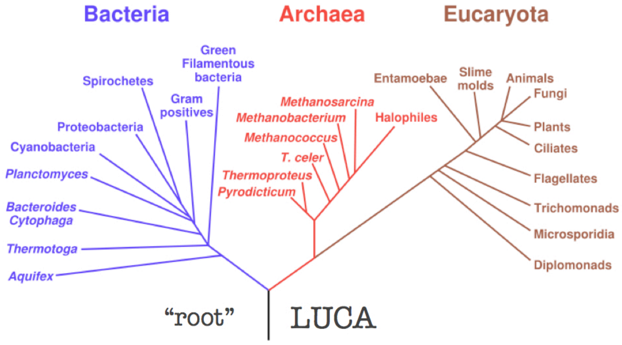
Search for the first living cells

- "Top-down" approach
  - From the study of present-day living organisms, we try to characterize the properties of the first terrestrial organisms proceeding backwards in evolution

- One of the methods being employed is the comparison of genetic sequences of present-day living organisms
  - Thanks to this comparative analysis, we can trace backwards the evolution at the molecular level
  - The results are visualized in the "phylogenetic tree", where the distances between different species are proportional to the differences found in the genetic sequences

The search for the “last common ancestor”

- The phylogenetic tree casts light on the properties of the last common ancestor of present-day living species
  - –Last (Universal) Common Ancestor
  - –also called Cenancestor
- The domain of Archea was discovered with this type of analysis
- Close to the “root” of the tree, we find thermophilic Archea and bacteria
  - – Did life originate in high-temperature environments, such as the hydrothermal vents at the bottom of the oceans?
    - The conditions in such environments may have been stable over geological time scales



The search for the “last common ancestor”

- We should not jump to conclusions on the origin of life from what we see at the root of the phylogenetic tree
  - Other forms of life, extinct in the course of the evolution, probably preceded the cenacestor
    - The living species that we see are probably a small fraction of the total number of species appeared in the course of evolution, that became extinct at some point
  - The interpretation of the phylogenetic tree is complicated by “horizontal gene transfer”
    - Exchange of genetic material that can take place even between bacteria