Origin of terrestrial life: “in situ” hypothesis

- To constrain the chronology and physical/chemical conditions of abiogenesis, we assume that terrestrial life originated on Earth (“in situ”)
  - This assumption is adopted by most authors but, strictly speaking, is only a working hypothesis
  - 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 an external origin of terrestrial life
  
  Although we do have evidence of organic material produced in space and delivered on Earth

Chronology of the origin of terrestrial life

- Assuming an origin “in situ”, 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 transition to habitable conditions sets an upper limit on the epoch of the origin of life
  - the oldest evidence of life found in the terrestrial crust
  - the age of the oldest traces of life set a lower limit on the epoch of the origin of life

- By comparing the time-scales of these events, we can estimate the epoch of life formation and the time interval available for life formation

Origin of life: the scientific approach

- The origin of terrestrial life is a central issue in astrobiology
  - We must cast light on the origin of terrestrial life in order to understand if life can originate in other astronomical environments
  - Habitability studies assume that life can be present in a given environment, without dealing with the problem of the origin of life

- The scientific approach
  - In the scientific approach, the origin of life is treated as a sequence of natural processes that leads to the formation of the first living cells starting from non biological chemical compounds

- Abiogenesis
  - The set of processes that leads to the origin of life is called abiogenesis

Chronology of the origin of life
Dating techniques

- Radiodating techniques play a fundamental role in studies of the early Earth.
- Thanks to these techniques, we can date with precision the age of the Solar System and Earth’s formation, and also the age of the oldest terrestrial rocks bearing signatures of past life.
- In practice, one compares 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:
  \[ ^{238}\text{U} (\tau = 4.5 \times 10^9 \text{ yr}), \ ^{235}\text{U} (\tau = 7.0 \times 10^8 \text{ yr}) \]

Age of formation of the Solar System

- The age of formation of the Solar System can be dated with accuracy from the analysis 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: \( \sim 4.50 \times 10^9 \text{ yr} \)
  - Oldest terrestrial rocks: \( \sim 4.45 \times 10^9 \text{ yr} \)
- 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 0.5 Gyr 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

- As a result of the tectonics, the oldest, well preserved crust material has ages of about $3.2 \sim 3.5 \times 10^9$ 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 for water on Earth

- Zircon crystals (ZrSiO$_4$) are found in detrital form in the oldest geological layers of the Earth
  - They are uranium-rich and can be used as geochronometers
- The analysis of the Jack Hills zircons (the oldest ones) suggests that liquid water was already present on Earth 4.4 Ga
- How diffuse was water at that epoch we do not know
  - Oceans probably appeared at a later stage
- The oldest zircons may have formed in the craters left by asteroid impacts on the primitive Earth, rather than via plate tectonics
  - (Kenny et al. 2016)
The “Late heavy bombardment” (LHB)

- The analysis of impact craters on the surfaces of the bodies of the inner Solar System indicates a long history of impacts, starting from the epoch of Solar System formation.

- The analysis of Moon 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.
  - The frequency and intensity of the impacts drastically decays between $4.1 \times 3.7 \times 10^9$ Ga.
  - The energy of the strongest impacts was sufficient to evaporate a present-day ocean.

- Two scenarios for the LHB:
  - If we extrapolate back in time the mass accumulated on the Moon by its impactors, the accretion of the Moon would have taken place at 4.1 Ga, which is completely unrealistic.
  - More likely, after an initial bombardment at the epoch of formation of the Earth and the Moon, there was a period of stability, followed by a late episode of bombardment (Ryder 2002).

“Late heavy bombardment” (LHB)

- Constrains models of the early evolution of the Solar System
  - A late migration of Jupiter and Saturn and a crossing of their 2:1 mean motion resonance would have triggered a dynamical instability ~600 million years after the origin of the planetary system (Gomes et al. 2005).

The “Late heavy bombardment” on Earth

- Evidence for the existence of the LHB starts to accumulate also from other bodies of the Solar System (not just the Moon).
- The LHB must have taken place also on Earth, even if we do not have direct geological evidences.

Implications of astrobiological interest

- The LHB may have delivered water and organic material on Earth at a late stage.
- The cumulative effect of the impacts may have made impossible for Earth to be habitable until the end of the LHB.
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
    Examples: sedimentary layers similar to present-day “stromatolites”
  - Geological layers of biological origin
    Examples: sedimentary layers similar to present-day “stromatolites”
- These methods only offer indirect evidences
  - Results should be taken with caution
  - Convincing evidence can be obtained by combining the results obtained from different methods

Oldest evidence for life on Earth

- The oldest, tentative, evidence are dated at about 3.8 Ga
  - Example: sedimentary rocks in the south-east of Greenland (Isua, Akilia)
    Based on the isotopic ratio $^{12}$C/$^{13}$C
- The oldest, more convincing, evidence are dated at about 3.2 - 3.5 Ga
  - Example: “Greenstone belts” in Australia (Pilbara) and South-Africa (Barbeton)
    - Isotopic ratios
    - Microfossils
    - Sedimentary layers suggesting the presence of diffuse life in shallow water, close to the littoral

Conclusions:

- If we consider the narrowest temporal window between the end of the LHB and the oldest evidence of life, the origin of life should have taken place around 3.8 - 3.9 Ga, on a relatively short time scale (~10^8 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 million years
  - Even if we consider the more robust evidences, life must have originated before 3.5 Ga, when it was already widespread
- These time scales can be relaxed by several hundred million years if we assume that life originated before the end of the LHB
  - Some authors claim that the life could emerge before the LHB
The “Panspermia” hypothesis

Some authors believe that the emergence of a phenomenon as complex as life requires time scales much larger than $10^8$ yr (perhaps comparable to the age of the universe).

If this argument is correct, life should have originated well before the formation of the Earth.

This is one of the motivations invoked in support of the “panspermia” theory, i.e. the hypothesis that life would have been delivered on Earth from space.

In the original version of the panspermia, bacterial spores driven by radiation pressure would spread in space, bringing life to Earth (S. Arrhenius 1908).

A revised version of this hypothesis has been later supported by F. Hoyle and C. Wickramasinghe.

Arguments used to support the hypothesis

Extraterrestrial organic material does exist and can be delivered on Earth.

Some terrestrial micro-organisms are potentially able to survive to the high dosis of radiation expected in case of space transportation (e.g., *Deinococcus Radiodurans*).

Arguments against the adoption of this hypothesis

There is no experimental confirmation of life being delivered on Earth.

The argument of the “short time scale” is weak; the time scales of chemical reactions are extremely short and there is no reason why life could not emerge from prebiotic chemistry in a few hundred million years.

Disadvantage of the “panspermia” hypothesis

By accepting the panspermia, we shift the problem of the origin of life to an unknown time and location.

As a result, we do not have a chemical/physical framework to test the processes of abiogenesis.

Interplanetary “Panspermia”

Weaker versions of the panspermia hypothesis have emerged in recent times.

Life may have originated in another planet and then transported to Earth by meteorites ejected by that planet.

Interplanetary panspermia is by far more plausible than interstellar panspermia as far as the transportation is concerned.

For instance, we do find meteorites of martian origin on Earth.

The time scales of interplanetary travel are relatively short.

Origin of life on Earth

In the rest of these lessons we will consider the origin of life in the context of the primitive Earth.

However, important steps of prebiotic chemistry are likely to have occurred outside Earth.