Chronology of the origin of life

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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 <u>sequence of natural processes that leads to the formation of the first living cells starting from non biological chemical compounds</u>
- Abiogenesis
  - The set of processes that leads to the origin of life is called *abiogenesis*

Origin of terrestrial life:
"in situ" hypothesis

- To contrain 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 <u>working hypothesis</u>
  - 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 and 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 <u>epoch of life formation</u> and the <u>time interval available for life formation</u>

Dating techniques

- Radiodating
  - 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}U (τ=4.5x10^9 yr), ^{235}U (τ=7.0x10^8 yr)

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:

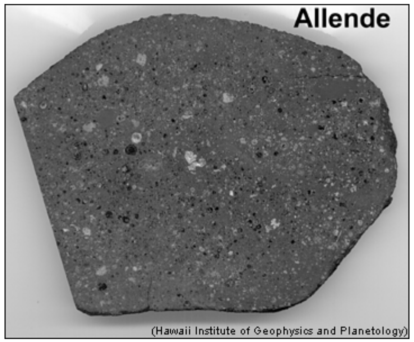
  4.57 x 10^9 yr

  - Example: Allende meteorite

    a type of chondritic meteorite

    classified as CV

    Felt in Mexico in 1969



Age of formation of the Solar System

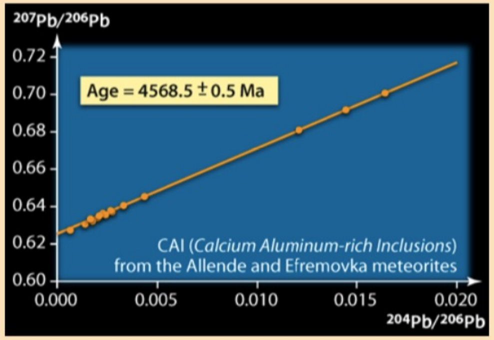


Fig. 2.1 (^{207}Pb/^{206}Pb) *versus* (^{204}Pb/^{206}Pb) isochron diagram for CAI (Calcium Aluminum-rich Inclusions) extracted from the Efremovka and Allende carbonaceous chondrites (Box 2.2 and Fig. 2.6 for the description of the dating method). In such a diagram, the age is proportional to the slope of the straight-line isochron. Here, the calculated age, is 4568.5 ± 0.5 Ma; by convention, this age is considered to be the starting point, "time zero" (t_0), for the formation of the Solar System. (After Bouvier *et al.*, 2007.)

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

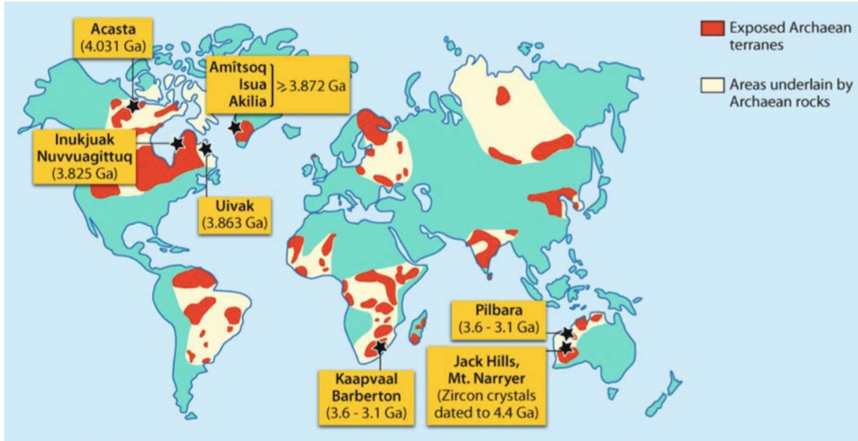
The oldest terrestrial rocks

- 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 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

The oldest terrestrial rocks

- As a result of the tectonics, 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 terrestrial rocks



From Gargaud et al. (2012)

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)

Impacts of minor bodies on the primitive Earth

- The impact craters on the bodies of the inner Solar System indicate a <u>long history of impacts</u>, starting from the epoch of Solar System formation

– Due to tectonics, the oldest impact craters are not visible on Earth
– Evidence for the impacts in the proximity of the Earth comes from the study of the Moon craters
– Evidence for nearby impacts is also accumulating from other bodies of the inner Solar System

– The impacts were likely the result of episodes of dynamical instability in the early evolutionary stages of the Solar System
– Dynamical instability led to the migration of small bodies from outer regions, richer in volatile material, to the inner regions, where rocky planets were formed

The "Late heavy bombardment" (LHB)

- The analysis of <u>Moon</u> impact craters suggests the existence of an episode with a large number of heavy impacts well after the formation of the Solar System
  – The frequency and intensity drastically decays between 4.1 e 3.7 x 10^9 Ga
  – The energy of the strongest impacts was sufficient to evaporate a present-day ocean

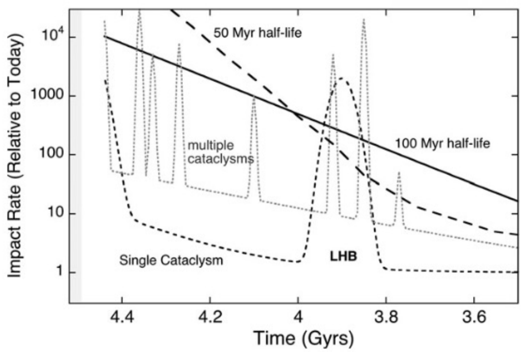
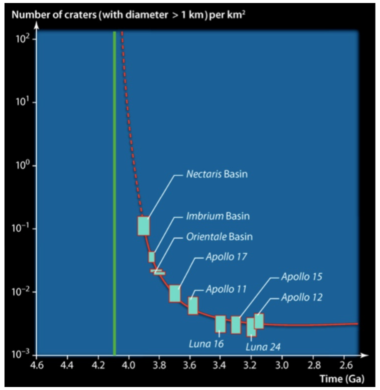
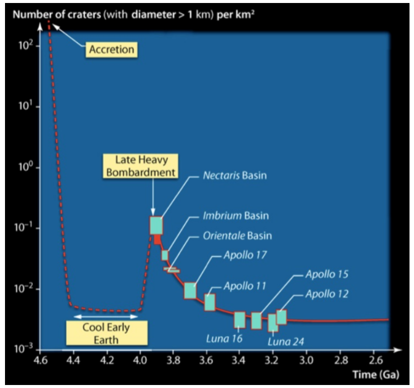


FIG. 2. Four possible scenarios for the LHB, calibrated to crater counts and surface ages at the Apollo landing sites. All scenarios except the 50 Myr half-life model are supported by the available data. Reprinted by permission from Springer Nature: Zahnle *et al.* (2007).

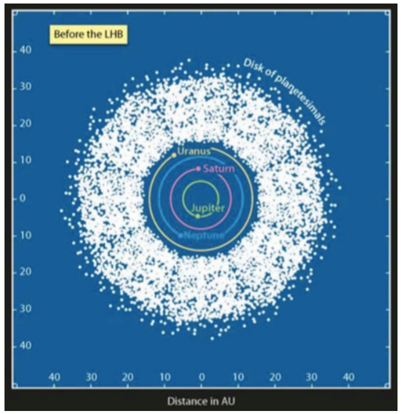
- Possible scenarios for the LHB
  – If we extrapolate back in time the mass accumulated on the Moon by its impactors, the accretion of the Moon would have taken place at 4.1 Ga, which is unrealistic
  – Another scenario is that, after an initial bombardment at the epoch of formation of the Earth and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

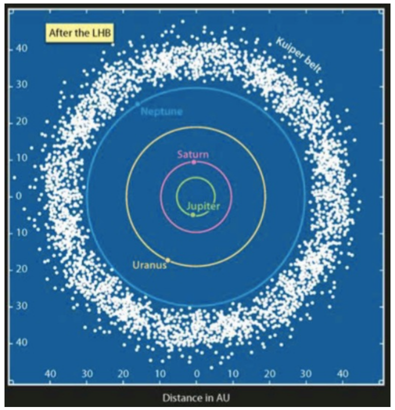




The "Late heavy bombardment" in the context of Solar System evolution

- If confirmed, sets remarkable constraints to evolutionary models
  – A late migration of Jupiter and Saturn and a crossing of their 2:1 mean motion resonance would have triggered a dynamical instability ~600 millon years after the origin of the planetary system (Gomes et al. 2005)





Impacts, habitability and delivery of volatiles

- According to some authors, the cumulative effect of the impacts may have delayed the habitability until the end of the LHB
- However, *the evidence for the LHB is not robust* and, in any case, the Earth may have been habitable before 4 Ga, without a total interruption of habitability conditions during the LHB
- The impacts of astronomical bodies rich in volatiles may have delivered water and organic material on the primitive Earth
- In particular, the LHB may have delivered water and organic material on Earth *at a late stage*, well after the formation of the Solar System

Summary of the habitability boundary

- The zircons with age 4.4 Ga show evidence of having been processed by liquid water
- Therefore the Earth could have been already habitable before 4 Ga, after the solidification of the magma and the onset of water oceans

- If the LHB did not interrupt the habitability, the temporal boundary for habitability conditions is ~4.4 Ga
- If the LHB did interrupt the habitability of the Earth, the upper boundary of continuous habitability is ~3.9 Ga

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

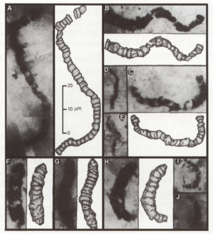
    Microfossils can be preserved thanks to the mineralization of organic matter of biological origin
  - Geological layers of biological origin

    Examples: sedimentary layers similar to 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

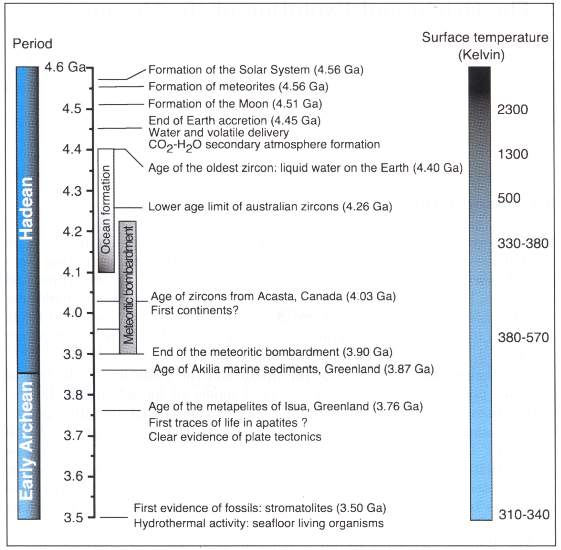
Oldest evidence for life on Earth

- 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 litoral



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



Summary of temporal constraints on the origin of terrestrial life

- Assuming that the LHB interrupted the habitability
  - If we consider 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 (~10^8 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 millon years
  - Even if we consider the more robust evidences at 3.5 Ga, life must have originated before 3.5 Ga , when it was already widespread
- Assuming that the LHB did not interrupt the habitability
  - The time scales can be relaxed by several hundred millon years
  - The Earth could have been habitable for almost 1 Gyr before life was able to emerge

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)

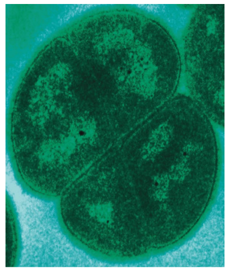
A revised version of this hypothesis has been later supported by F. Hoyle and C. Wickramasinghe

The "Panspermia" hypothesis

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 millon 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