Extremophiles
Physico-chemical limits of terrestrial life

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Physico-chemical limits of terrestrial life

The terrestrial biosphere is more extended than we thought in the past

Studies of microbiology keep finding echosystems in environments that once used to be considered not habitable

Terrestrial life is found in habitats characterized by a broad spectrum of physical and chemical conditions

Striking examples are the echosystems found in the deep ocean, but there are many other examples

Extremophiles

- Organisms living in environments with extreme physico-chemical conditions are called extremophiles
  The physical and/or chemical conditions of such environments are extreme from an anthropocentric point of view
- Extremophiles cast light on the physico-chemical limits of life
  Understanding such limits is essential to define the limits of "habitability"
- Extremophiles are also important for biotechnology applications
  For example, the PCR (Polymerase Chain Reaction) uses an enzyme originally isolated from the extremophilic bacterium (*Thermus aquaticus*)

Importance of extremophiles in astrobiology

Extremophiles indicate that life can potentially exist also in the extreme environmental conditions found in planets and satellites of the Solar System and extrasolar planets

Extremophiles cast light on the early evolutionary stages of terrestrial life, and hence on the origin of life, since many of them are among the oldest organisms that we know

Classification of extremophiles

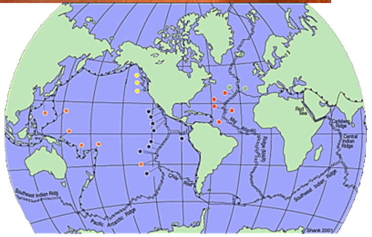
- Extremophiles are classified according to the physical or chemical property they are adapted to
  - Temperature
    - Thermophiles & hyperthermophiles (high temperature)
    - Psycrophiles (low temperature)
  - pH
    - Acidophiles, alcalophiles
  - Pressure
    - Barophiles (high pressure)
  - Salinity
    - Halophiles (high salinity)
  - Humidity
    - Xerophiles (low humidity)
  - Ionizing radiations
    - Radioresistant

Extremophiles

- Many extremophiles are adapted to more than one physico-chemical property
  - Examples
    - Some hyperthermophiles are also adapted to extreme values of pressure
    - Radioresistant microrganisms are usually resistant to dehydration conditions

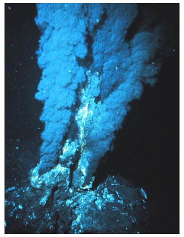
High temperatures

- Thermophiles
  - –Optimal growth at ~ 40 °C o higher temperature
- Hyperthermophiles
  - –Optimal growth at ~ 80°C or higher

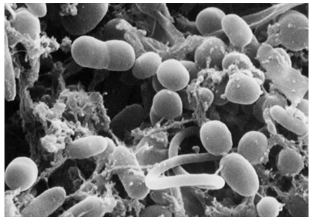


- Examples of habitats
  - –Geisers or fumaroles
    - Yellowstone park (USA)
      - Bacterial mats
    - In addition to the temperature, also the acidity is extreme
  - –Hydrothermal vents
    - Deep ocean sites of volcanic activity

High temperatures

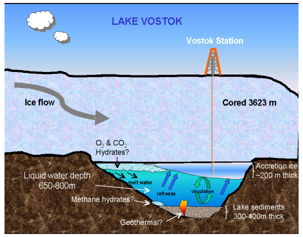


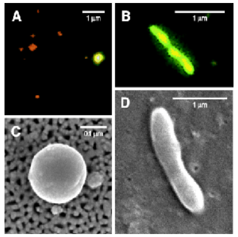
- Deep ocean volcanic sources
  - –"hydrothermal vents"
      - Temperatures larger than 370 °C
      - Pressures between 70 and 300 bar
    - Echosystem without solar light
    - Energy is extracted from reactions of oxidation-reduction
      - Chemiosynthetic archaeobacteria
        - First echosystems of this type discovered in 1977 in the ocean floors near Galapagos islands; then found in other similar locations



Low temperatures

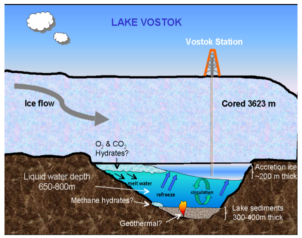
- Psycrophiles
  –Optimal growth at ~ 15 °C or lower temperatures
- Examples of extreme habitats
  –Permafrost
  –Antarctica
  About 100 subglacial lakes
  Example: Vostok lake
  An environment under investigation, with very low temperatures, lack of solar radiation, isolated from the rest of the biosphere





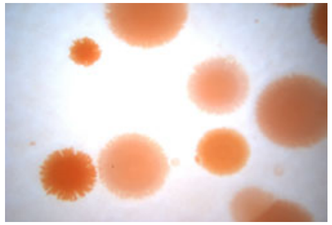
Importance of extremophiles in astrobiology

- Subglacial lakes in Anctartica are an ideal laboratory for studies of astrobiology
  –Testing techniques to prevent biological contamination of isolated environments
  –Testing techniques to search for life in icy environments in the Solar System
  Example: Europa (icy satellite of Jupiter)

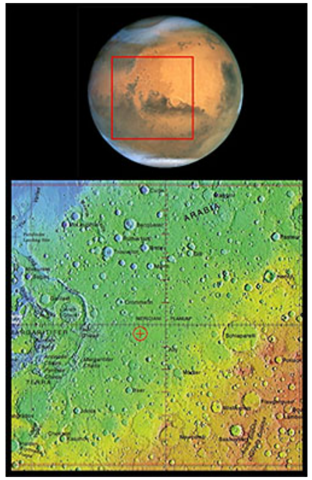


Salinity

- Halophiles
  – Live in high salt concentrations, up to 25%
  – Examples of salty environments
    Dead Sea
    Great Salty Lake (Utah)
  These environments are also characterized by high levels of irradiation to near UV photons



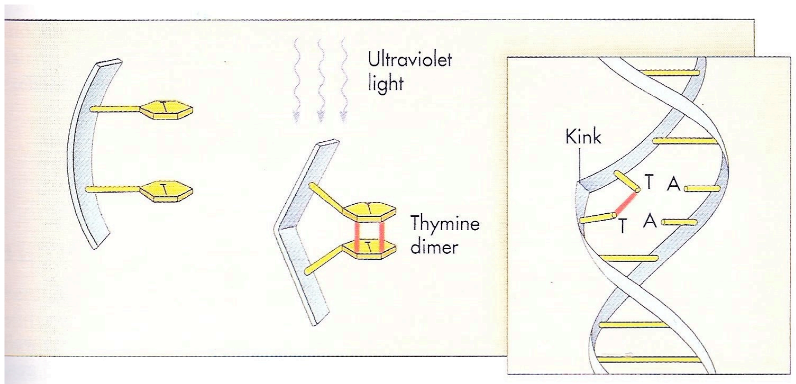
- Importance of halophiles in astrobiology
  – Example of salty environment in the Solar System
    Flatlands in Mars with characteristics of an ancient salty lake
    Meridiani Planum



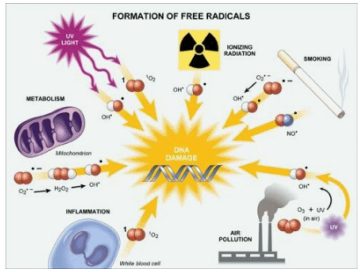
Ionizing radiation and life

- Ionizing radiation produces biological damages
  - Habitable environments must be protected by ionizing radiation
- UV photons and high energy particles produce different type of damages
- The most critical damages concern the DNA structure
  - UV photons typically damage only one of the two DNA strands
  - High energy photons and particles can trigger damages to both DNA strands
- DNA damages can be letal or may induce genetic mutations

- Biological effects of <u>ultraviolet</u> radiation
  - <u>Ultraviolet</u> radiation <u>does not ionize</u> biological atoms or molecules
  - However, UV radiation makes reactive some nucleobases
    - If reactive nucleobases are adjacent, they can chemically tie to each other, creating a “kink” in the DNA strand
    - The “kink” can block the DNA replication, inducing a letal damage



- Biological effects of high energy particles, X rays and γ rays
  - High energy events <u>ionize</u> atoms and molecules
    - Most of the times the direct damage takes place on the water molecules, i.e. the liquid substrate of biological molecules
      - Extremely reactive molecular species, called “free radicals”, are created as a result of the ionization events
    - Most of the DNA damage is done by the free radicals, rather than direct ionization of DNA molecules



High energy particles or photons, through the action of free radicals, can damage <u>both strands</u> at a given location of the DNA

Repair mechanisms of ionizing radiation

Resistance to ionizing radiation is provided by mechanisms of DNA reparation

- If the rate of mutations is sufficiently small and the damage is limited to one strand, natural mechanisms of DNA reparation may efficiently repair the damage
  - In practice, the information present in the damaged strand is recovered from the complementary strand
  - This type of DNA reparation is common among different forms of terrestrial life
- When the rate of mutations is high and both strands of DNA are damaged at the same location, some extremophiles are still able to recover the genetic information and repair the DNA

Radioresistant microrganisms

- Example: *Deinococcus Radiodurans*

  Can survive to a dosis of 5000 Gy or larger

  »1 Gy = 1 Gray = 1 joule / kg of mass

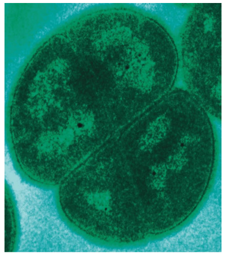
  –For comparison, 10 Gy is letal for man

  This organism has multiple copies of its DNA and complex mechanisms of DNA reparation

  Otherwise, this organism is similar to the rest of terrestrial life from the genetic and biochemical point of view

  –Unlikely to be of extraterrestrial origin, as suggested by some authors

–In addition to *Deinococcus Radiodurans*, other types of radioresistant microrganisms are known, both among archaea and bacteria



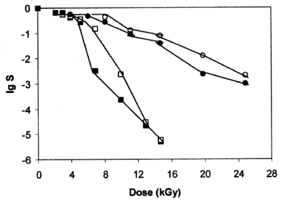
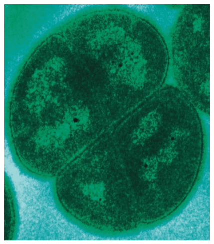


Fig.2. Gamma radiation survival curves of the type strain *Rubrobacter radiotolerans* (closed circle), strain RSPS-4 (open circle), type strain *Rubrobacter xylanophilus* (closed squares) and strain RSPS-21 (open squares) (Ferreira et al, 1999).

Importance of radioresistant organisms in astrobiology

- Habitability of planetary surfaces exposed to ionizing radiation
- Space colonization (e.g., establishing terrestrial life outside Earth, possibly via terraforming)
  - [not discussed here]
- Transportation of life in space
  - Panspermia theories



Multicellular extremophiles

- Most extremophiles are microorganisms
- However, rare cases of multicellular extremophiles are known
- Example: tardigrades ("water bears")
  - Typical size: ~ 0.5 mm
  - Survive extreme conditions of temperature, pressure, dehydration, ionizing radiation
  - Capable of reversibly suspending their metabolism and going into a state of cryptobiosis
  - Several species of tardigrade survive in a dehydrated state for nearly 10 years
  - Extensively studied on board of the International Space Station (ISS) and in other space experiments

Thermal limits of habitability

- The wide range of adaptation of extremophiles to a broad interval of temperatures makes hard to define thermal limits of planetary habitability
- A careful distinction of the thermal response of different types of terrestrial organisms shows that it is possible to define relatively narrow temperature limits for
  - the generation of atmospheric biomarkers
  - the development of complex (multicellular) life

Thermal limits for terrestrial life

- Distinction of different types of thermal limits
  - Survival, metabolism, completion of the life cycle (reproduction)

Clarke (2014)

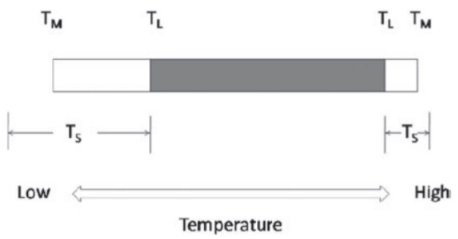


Fig. 2. Temperature thresholds for life on Earth. T_L: thermal limits for completion of the life cycle; T_M: thermal limits for metabolism; T_S: thermal limits for survival. The shaded portion shows the temperature range over which the life cycle can be completed, and defines the thermal limits for the continued existence of a species over generations.

Thermal limits for complex life

The thermal limits become narrower
with increasing complexity of the organisms

Low-temperature limits

Taxon	T_L (°C)	T_S (°C)
Archaea		
	−16.5	nd
Bacteria		
	~−20	<−196
Eukarya		
Unicellular algae	~−8	nd
Yeasts	~−20	<−196
Lichens	−10[a]	≤80
Mosses	nd	−30
Angiosperms	~0[a]	~−70
Terrestrial invertebrates	~0	<−196
Freshwater invertebrates	~0	nd
Marine invertebrates	~−2	~−2
Ectothermic vertebrates	~−2	~−2
Endothermic vertebrates	nd	nd

nd: no data.

High-temperature limits

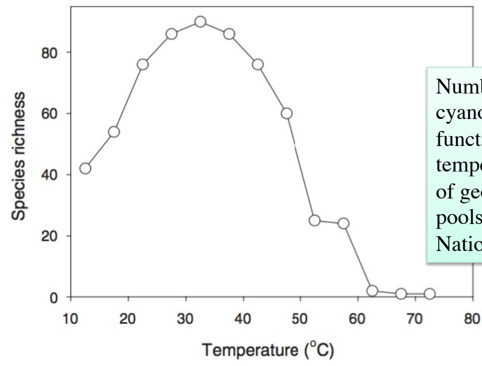
Taxon	T_L (°C)	T_S (°C)
Archaea		
M. kandleri	122	<130
Bacteria		
G. ferrireducens	100	nd
Eukarya		
Unicellular algae	60	nd
Yeasts	60–62	nd
Lichens	~45[a]	nd
Macroalgae	~45	nd
Mosses	~50[a]	nd
Angiosperms	65	nd
Terrestrial invertebrates	~60	~70
Freshwater invertebrates	~46	nd
Marine invertebrates	>42[a]	~90
Ectothermic vertebrates	~46	nd
Endothermic vertebrates	nd	nd

nd: no data.

Clarke (2014)

Thermal limits for the generation of atmospheric biomarkers

- Plants and cyanobacteria are the main contributors to oxigenic production in Earth's atmosphere
- The thermal limits of most plants and cyanobacteria are bracketed by the temperature interval 0°C ≲ T ≲ 50°C



Number of species of cyanobacteria as a function of water temperature across a range of geothermally heated pools in Yellowstone National Park

Thermal limits for atmospheric biosignatures and complex life

The temperature interval
0°C ≲ T ≲ 50°C
brackets the thermal limits for the active metabolism and reproduction of multicellular poikilotherms

Poikilotherms: organisms whose body temperature and functioning of all vital processes is directly affected by the ambient temperature

The same interval applies to the photosynthetic production of oxygen

Oxygen is important as a possible atmospheric biomarker
Oxygenic metabolism is believed to be an essential ingredient of complex life

(Silva et al. 2017)