Astrobiology

Lecture 6

Extremophiles: physico-chemical limits of life

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

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

Studies of microbiology have found echosystems in environments with extreme conditions, not considered habitable in the past

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 can also be 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 in extreme conditions in Solar-System bodies and extrasolar planets
- Many extremophiles are among the oldest organisms that we know and so they cast light on the early organisms, closest to the origin of life

Unicellular and multicellular extremophiles

- Most extremophiles are unicellular, often *archaea*
- A few multicellular extremophiles are also known

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

Poly-extremophiles

- Many extremophiles are adapted to more than one physico-chemical property

    Examples

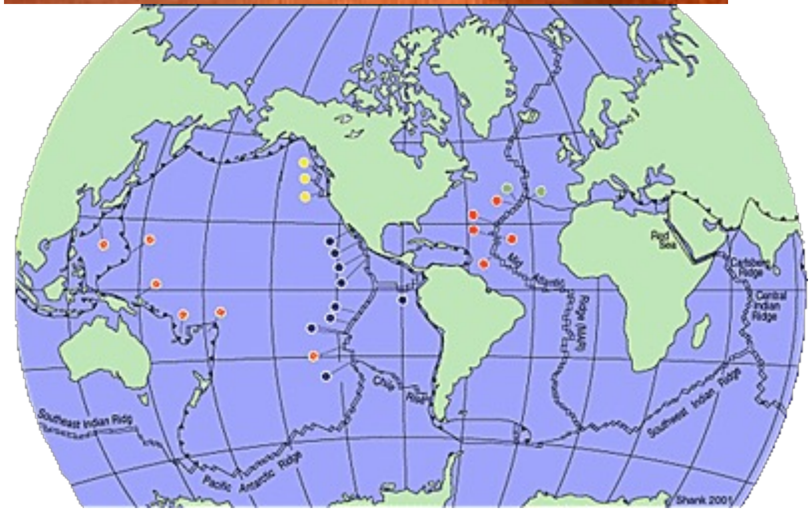
        Some hyperthermophiles are also adapted to extreme values of pressure

        Radioresistant microrganisms are also resistant to dehydration conditions in most cases

High temperatures

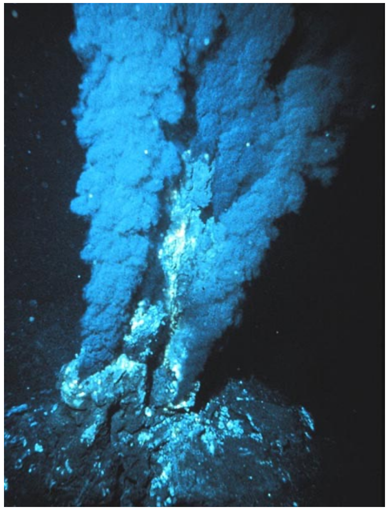
- Thermophiles
  - – Optimal growth at ~ 40 °C o higher temperature
- Hyperthermophiles
  - – Optimal growth at ~ 80°C or higher

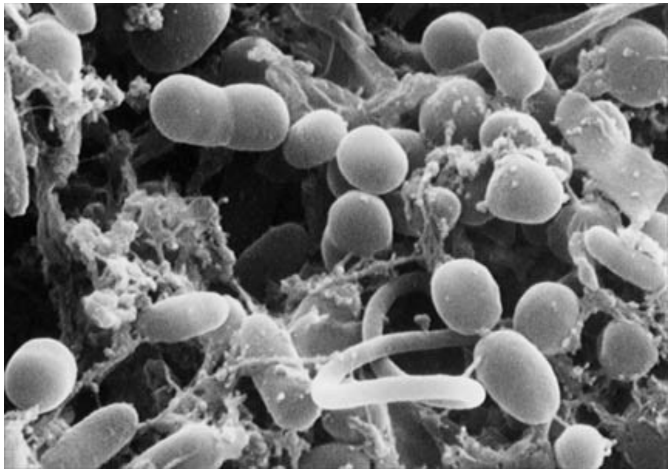
- Examples of habitats
  - – Geisers or fumaroles
    - Yellowstone park (USA)
      - Bacterial mats
    - In addition to the temperature, also the acidity is extreme
  - – Hydrothermal vents
    - Deep ocean sites of volcanic activity



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

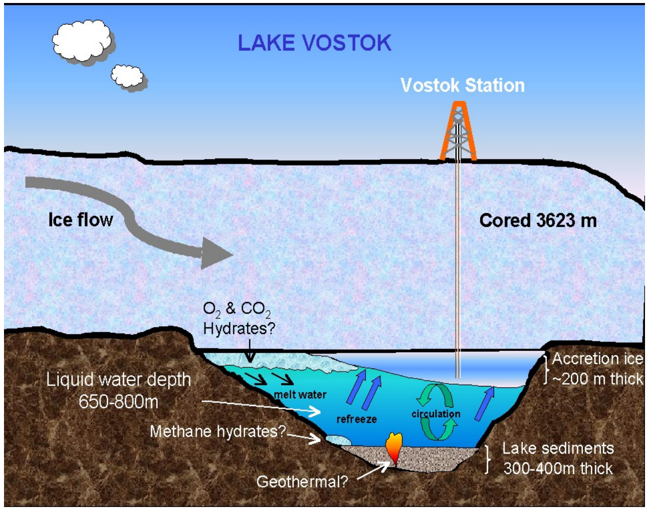
- Psycrophiles
  – Optimal growth at ~ 15 °C or lower T

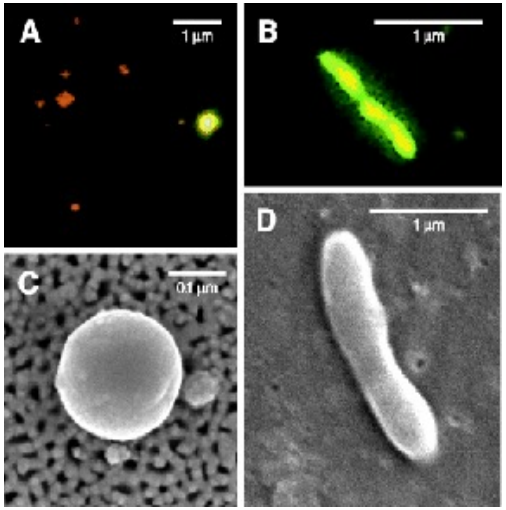
- Examples of extreme habitats
  –Permafrost
  –Antarctica

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

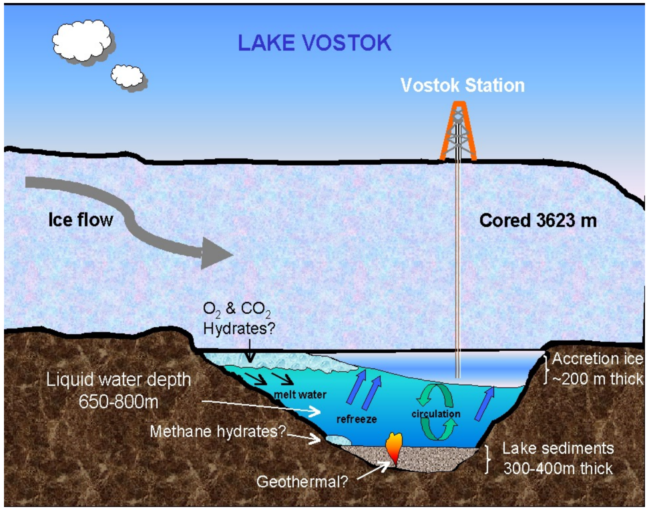




Importance of extremophiles in astrobiology

- 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)



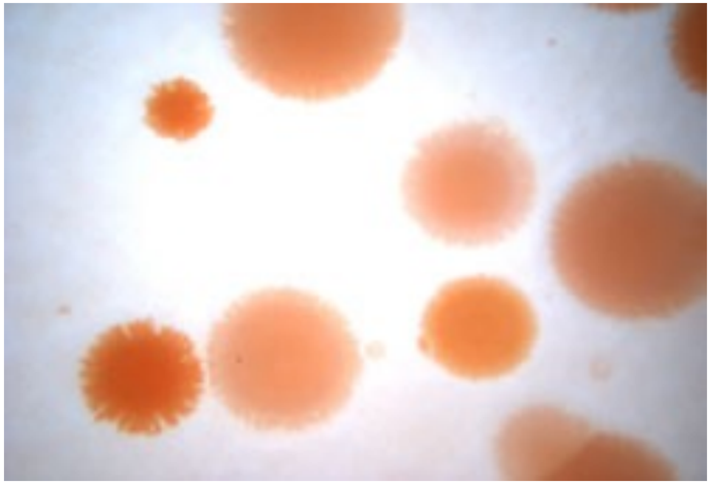
Salinity

- Halophiles
  - Live in high salt concentrations, up to 25%
  - Examples of salty environments

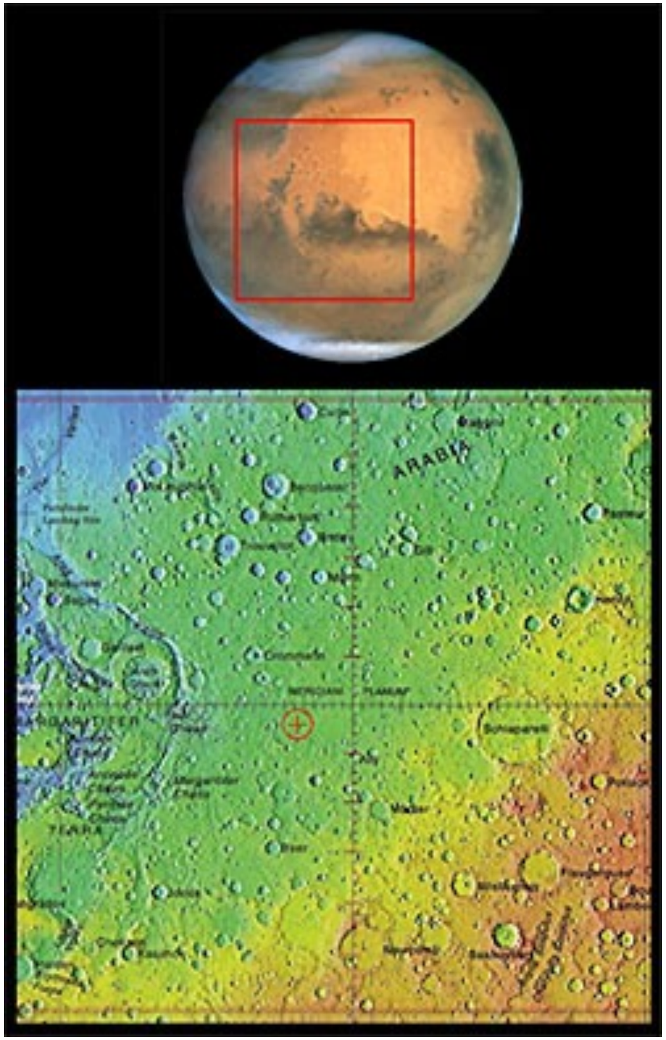
    Dead Sea

    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



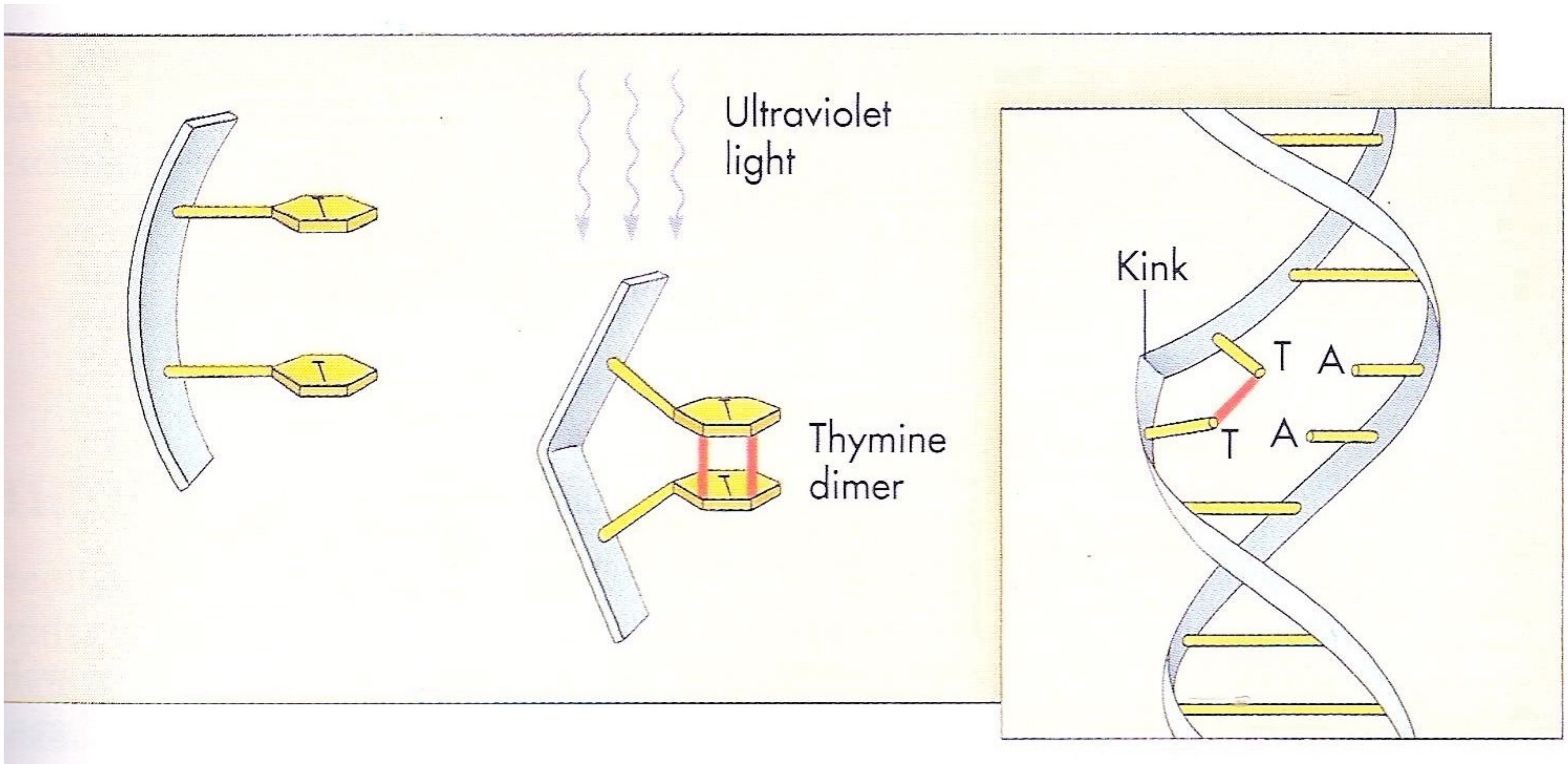
Ionizing radiation and life

- 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 ultraviolet radiation
  - Ultraviolet radiation does not ionize 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

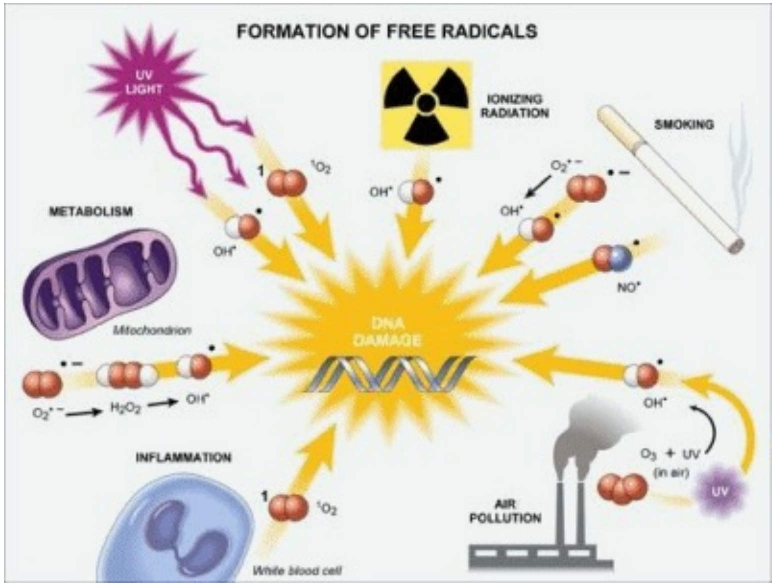


- Biological effects of high energy particles, X rays and γ rays
  - High energy events ionize atoms and molecules

    Most of the times the direct damage takes place on the water molecules that form the liquid substrate of biological molecules

    Extremely reactive molecular species ("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 both strands at a given location of the DNA

Repair mechanisms of ionizing radiation

Resistance to ionizing radiation is provided by mechanisms of DNA reparation

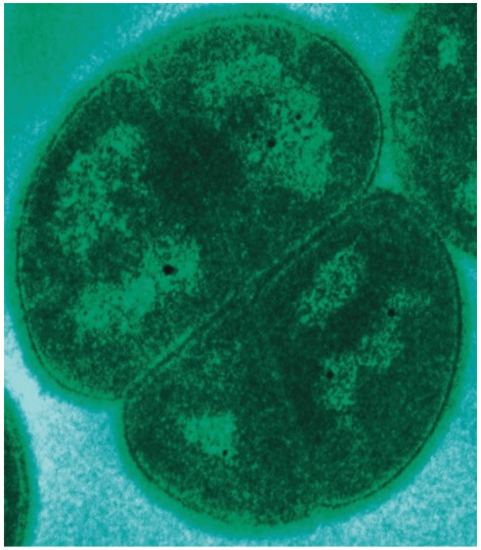
- If the rate of mutations is sufficiently small and the damage is limited to one strand, natural mechanisms of DNA reparation may efficiently repair the damage
  - In practice, the information present in the damaged strand is recovered from the complementary strand
  - This type of DNA reparation is present in many organisms

- 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
  - A part from these remarkable properties, 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 the past

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



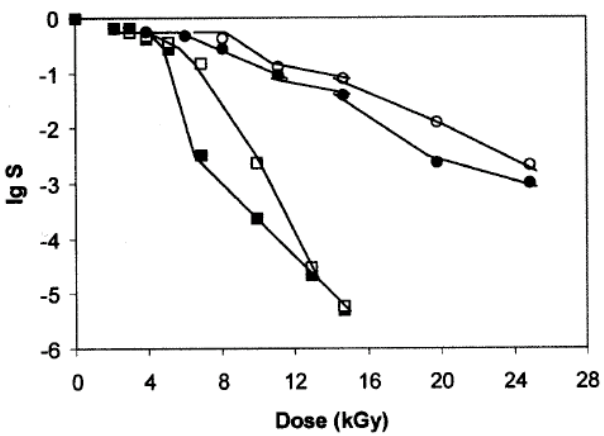
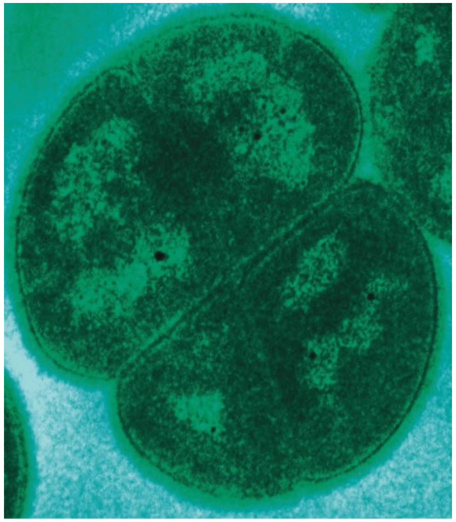


Fig.2. Gamma radiation survival curves of the type strain *Rubrobacter radiotolerans* (closed circle), strain RSPS-4 (open circle), type strain *Rubrobacter xylanophilus* (closed squares) and strain RSPS-21 (open squares) (Ferreira et al, 1999).

Importance of radioresistant organisms in astrobiology

- Habitability of planetary surfaces exposed to ionizing radiation
  - E.g., rocky planets without a protecting atmosphere or magnetic field
- Space exploration
  - Radiation dose during travel and on planetary surface
- Space colonization
  - Establishing terrestrial life outside Earth, possibly via terraforming
- Transportation of life in space
  - Panspermia theories



Multicellular extremophiles

- 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

- Life processes have a strong dependence on temperature
- The temperatures of the environments in which cryophiles and hyperthermophiles are found can be used to set lower and upper thermals limits to terrestrial life
- By comparing the thermal response of different types of organisms we can define 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)

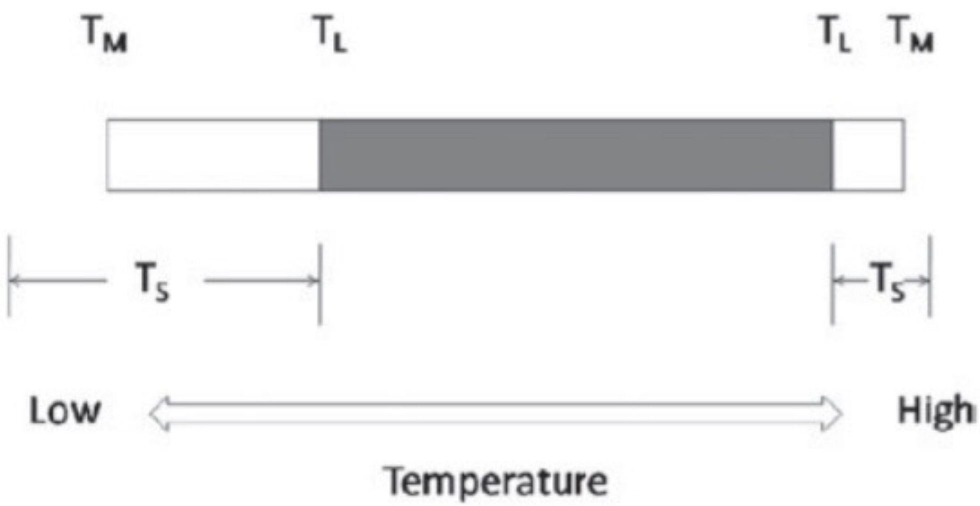


Fig. 2. Temperature thresholds for life on Earth. T_L: thermal limits for completion of the life cycle; T_M: thermal limits for metabolism; T_S: thermal limits for survival. The shaded portion shows the temperature range over which the life cycle can be completed, and defines the thermal limits for the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

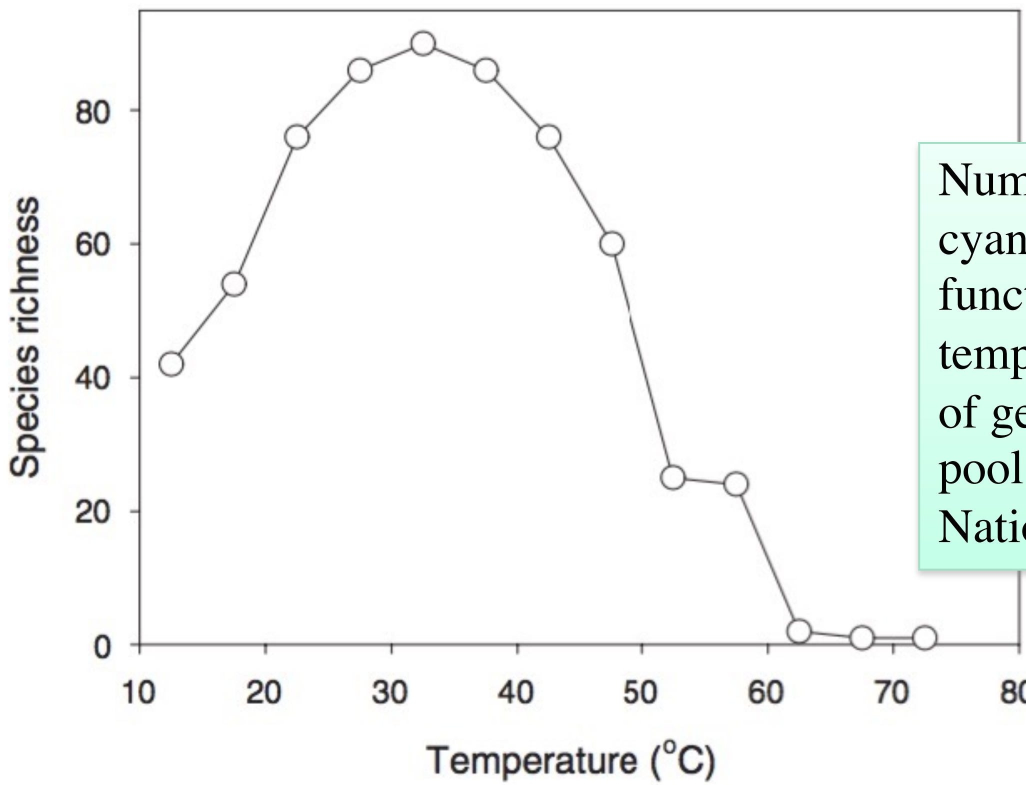
Taxon	T_L (°C)	T_S (°C)
Archaea		
M. kandleri	122	< 130
Bacteria		
G. ferrireducens	100	nd
Eukarya		
Unicellular algae	60	nd
Yeasts	60–62	nd
Lichens	∼ 45[a]	nd
Macroalgae	∼ 45	nd
Mosses	∼ 50[a]	nd
Angiosperms	65	nd
Terrestrial invertebrates	∼ 60	∼ 70
Freshwater invertebrates	∼ 46	nd
Marine invertebrates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

nd: no data.

Clarke (2014)

Thermal limits for the generation of atmospheric biosignatures

- 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 $0^{o}C \lesssim T \lesssim 50^{o}C$



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 (multicellular) life

The temperature interval

$$0^{o}C \lesssim T \lesssim 50^{o}C$$

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 biosignature
Oxygenic metabolism is believed to be an essential ingredient of complex life

(Silva et al. 2017)