Introduction to Astrobiology

Chapter 2
Habitable environments

- Habitable environments
  - An environment that has the capability of sustaining forms of life is said to be "habitable"
  - The definition of habitability is related to the definition of life

- The habitability is influenced by many factors

  Here we focus our attention on
  - Physical/chemical conditions of the environment
  - Presence of energy sources
  - Protection from ionizing radiation

- Habitability of the Earth

  – The Earth is the only reference that we have to test the concept of habitability by investigating the distribution of life in natural environments characterized by a broad range of physical and chemical conditions

  – In the last decades, the resistence/adaptation of life has started to be tested also in artificial space environments, such as the International Space Station

  – Here we will focus only on the first aspect

Earth habitability: energy sources

- The existence of energy sources is an essential requirement of any habitable environment
  – Heterotrophs adquire their energy from autotrophs
  – Autotrophs adquire their energy directly from the environment

- Any habitabile environment must provide energy sources to the autotrophs
  – Heterotrophs use, by definition, the carbon and energy fixed by autotrophs

- Terrestrial autotrophs adquire energy in two ways:
  – redox reactions (oxydizing-reducing reactions)
  – photosynthesis

Energy sources for terrestrial life: oxidation-reduction reactions

- There are many different types
  - Adapted to the chemical elements that are abundant in specific environments
- Examples
  - Methanogenesis

    Example of oxydation-reduction reaction in which hydrogen is oxydized while carbon dioxide is reduced

    Reaction scheme:

    $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

    Employed by autotroph organisms in the deep ocean "hydrothermal vents"

    Provides energy, while fixing the carbon that becomes available for further synthesis of organis molecules
  - Metabolism based on sulphur

    Probably very ancient

    Examples of microrganisms:

    Thiobacillus thiooxidans, Sulfolobus acidocaldarus

    Example of reaction scheme:

    $6\,CO_2 + 12\,H_2S \rightarrow C_6H_{12}O_6 + 6\,H_2O + 12\,S$ + energia

    Example of habitat: sulphuric caves

Energy sources for terrestrial life: photosynthesis

Photosynthesis converts incoming stellar photons into chemical energy.

It is an extremely complex mechanism that takes places in different steps, involving the contribution of many proteins and small molecules

Only part of the reactions are triggered by light

An important part of the cycle is light-independent

There are different types of photosynthesis, the most diffuse in present-time terrestrial life is the <u>oxygenic</u> photosynthesis

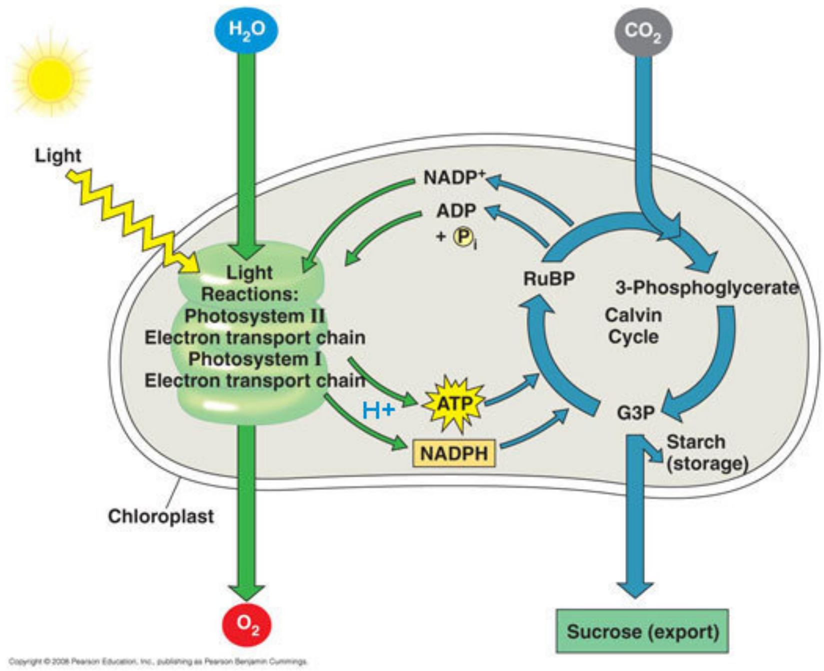
It is the main sources of organic carbon and of oxygen used by aerobic organisms

The overall budget of reactant and products of reaction in the oxygenic photosynthesis can be expressed in the <u>idealized scheme of reaction</u>

$$CO_2 + H_2O + h\nu \rightarrow (CH_2O) + O_2$$

(CH_2O) represents a carbohydrate, mainly saccarose or amid

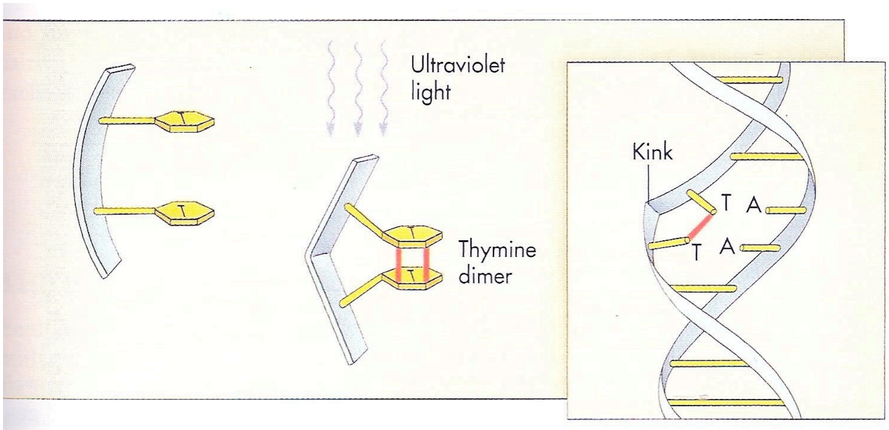
Energy sources for terrestrial life: oxygenic photosynthesis



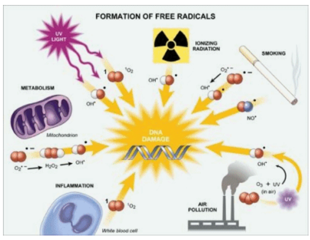
Biological damages due to ionizing radiation

- 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
  - Natural 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



- 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, 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

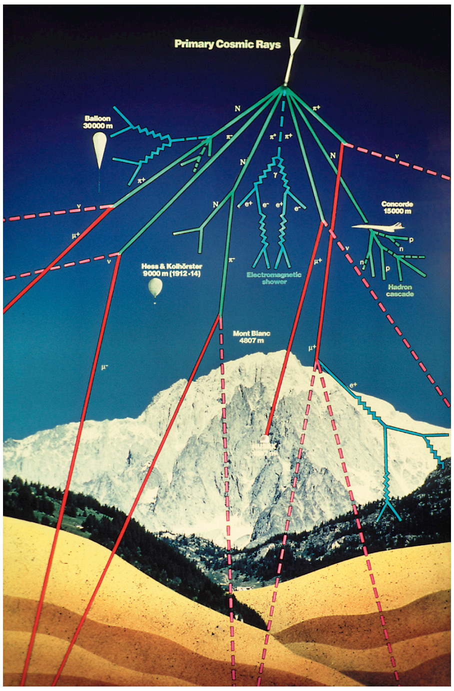


High energy particles or photons, through the action of free radicals, can damage both strands at a given location of the DNA

- The damage on both strands makes it impossible to recover the genetic information and therefore to repair the DNA
- However, some microrganisms, such as the *Deinococcus Radiodurans*, are able to recover the genetic information also in this case, thanks to the presence of multiple copies of their DNA

Earth habitability:
protection from ionizing radiations

- The Earth is exposed to different types of ionizing radiation
  - In a broad sense, ionizing photons and particles are called "ionizing radiation"
- Ultraviolet radiation
  - Originated from the Sun and from the interstellar radiation field
- Cosmic rays
  - High energy particles, mostly protons and alpha particles, originated in the Sun and Galactic supernovae
  - Primary cosmic rays produce cascades of secondary particles by interacting with the Earth atmosphere



Protective effect of the Earth atmosphere

- Ultraviolet photons
  - The ozone layer in the Earth atmosphere is an efficient absorber of ultraviolet photons, shielding the surface of the planet from this type of ionizing radiation
  - The production of O_3 is due to the photodissociation of O_2 in the high atmospheric layers, followed by the interaction of the O radicals with undissociated O_2 molecules
- Cosmic rays
  - The atmosphere converts high-energy primary cosmic rays into secondary particles of lower energy
  - Typically, a primary proton collides with a molecule of the air, giving rise to an "air shower" of charged mesons which decay into other particles

Habitability of the Earth: Extreme limits of physical/chemical conditions to which life can be adapted

Extremophile organisms

Terrestrial habitats

- The terrestrial biosphere is more extended than we thought in the past
  - Studies of microbiology keep finding echosystems in terrestrial environments that once used to be considered not habitable
    - Striking examples are the echosystems found in the deep ocean, but there are many other examples

- The physical and/or chemical conditions of such environments are extreme from an anthropocentric point of view
  - The organims that populate such echosystems are called <u>extremophiles</u>
  - Most, but not all, of them are microorganisms

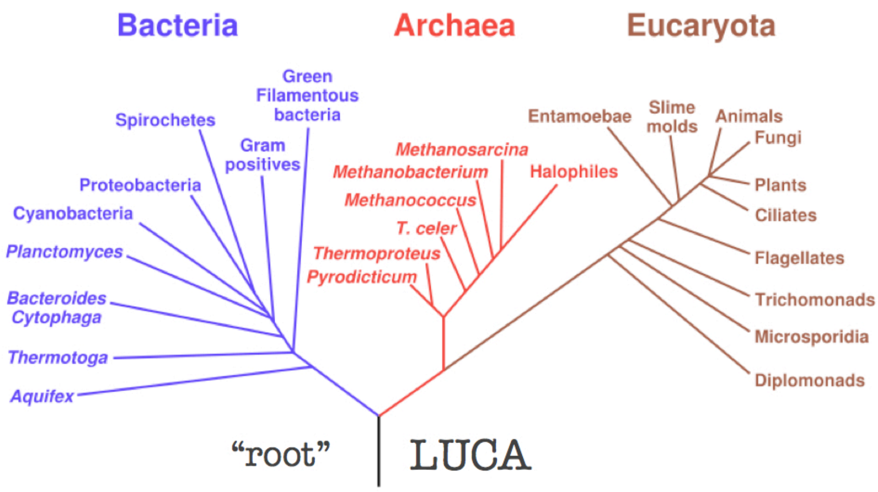
Importance of extremophiles in astrobiology

Extremophiles prove that life can in principle exist also in the extreme environmental conditions found in planets and satellites of the Solar System; extrasolar planetary systems

Extremophiles cast light on the early evolutionary stages of terrestrial life, and hence on the origin of life, since many of them belong to the most ancient organisms that we know

[Apart from astrobiology, extremophiles are very important for practical applications, not discussed here]

Extremophiles and the philogenetic tree of life



Classification of extremophiles

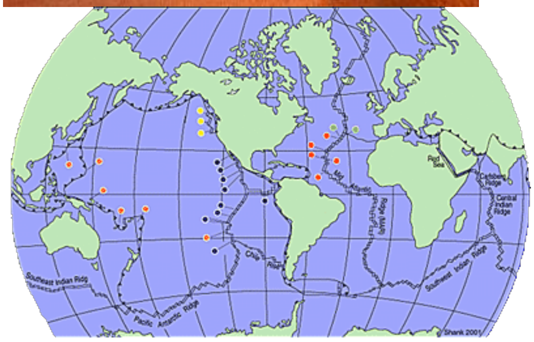
- Extremophiles are classified according to the physical or chemical property they are adapted to
  - Temperature
    - Thermophiles & hyperthermophiles (high temperature)
    - Psycrophiles (low temperature)
  - pH
    - Acidophiles, alcalophiles
  - Pressure
    - Barophiles (high pressure)
  - Salinity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

Extremophiles

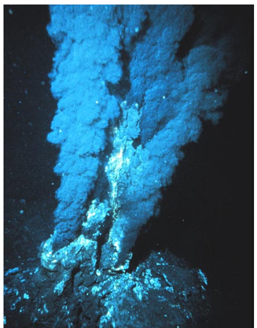
- Many extremophiles are adapted to more than one physico-chemical property
  - Examples
    - Some hyperthermophiles are also adapted to extreme values of pressure
    - Radioresistant microrganisms are also resistant to dehydration conditions

High temperatures

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



- Examples of environments hosting thermophiles
  - –Geisers or fumaroles
    - Yellowstone park (USA)
      - Bacterial mats
    - In addition to the temperature, also the acidity is extreme
  - –Deep ocean sites of volcanic activity
    - “hydrothermal vents”



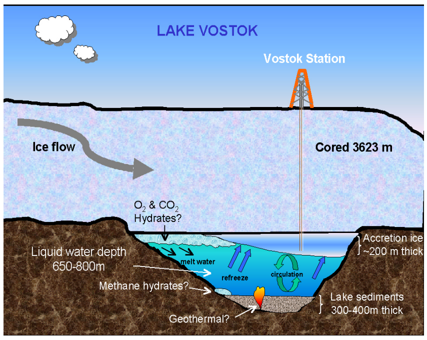
High temperatures

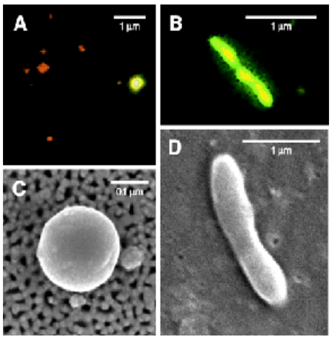
- Deep ocean volcanic sources
  - –“hydrothermal vents”
      - Temperatures larger than 370 °C
      - Pressures between 70 and 300 bar
    - Echosystem without solar light
    - Energy is extracted from reactions of oxydation-reduction
      - Chemiosynthetic archeobacteria
        - First echosystems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

- Importance of (hyper)-thermophiles
  - –Organism classifications based on molecular biology suggest that they are among the less evolved
    - Among known species, they are the closest to the origin of life

Low temperatures

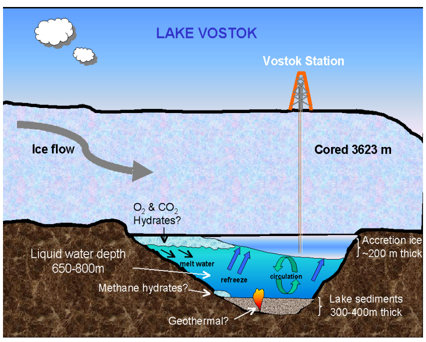
- Psycrophiles
  - –Optimal growth at ~ 15 °C or lower temperatures
- Examples of extreme habitats
  - Permafrost
  - Antarctica
    - About 100 subglacial lakes
    - Vostok lake
      - Very low temperatures, lack of solar radiation, isolated from the rest of the biosphere



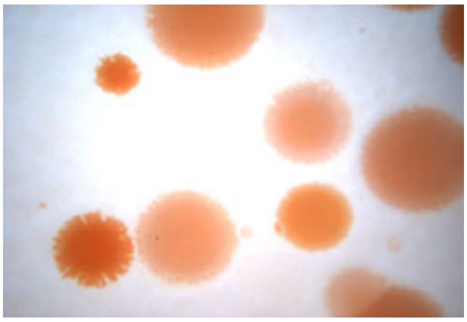


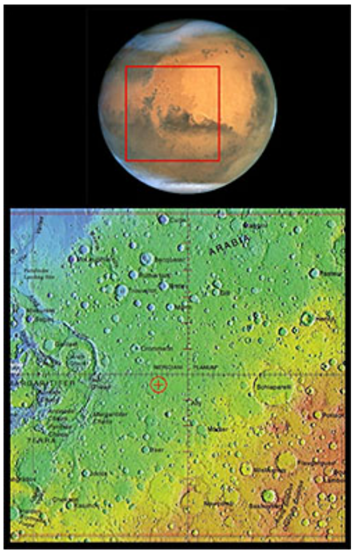
Low temperatures

- 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



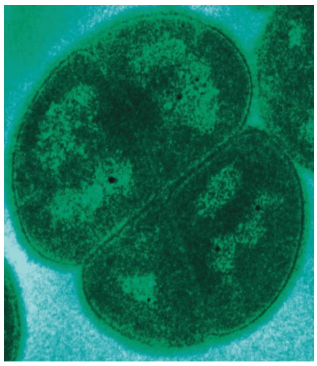


- Halophiles
  - Adapt to salt concentrations, up to 25%
  - Examples of salty environments
    - Dead Sea
    - Great Salty Lake (Utah)

    These environments are also characterized by high levels of irradiation to nearby UV photons
- Importance in astrobiology
  - Example of salty environment in the Solar System

    Flat lands in Mars with characteristics of an ancient salty lake
    - Meridiani Planum

Ionizing radiation



- 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 organisms is similar to the rest of terrestrial life from the genetical and biochemical point of view
      - –Unlikely to be of extraterrestrial origina, as suggested by some authors
  - In addition to *Deinococcus Radiodurans*, other types of radioresistant microrganisms are known, both among archea and bacteria

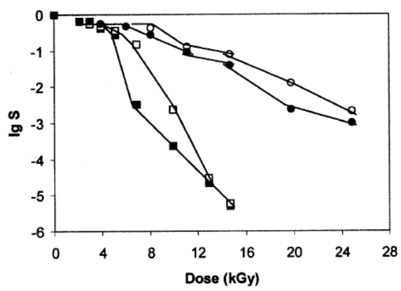
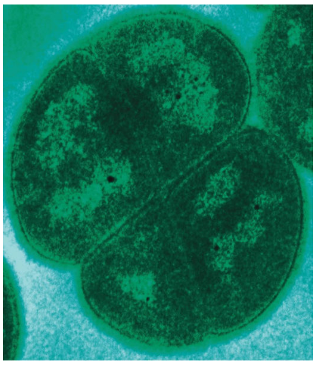


Fig.2. Gamma radiation survival curves of the type strain *Rubrobacter radiotolerans* (closed circle), strain RSPS-4 (open circle), type strain *Rubrobacter xylanophilus* (closed squares) and strain RSPS-21 (open squares) (Ferreira et al, 1999).

Importance of radioresistant organisms in astrobiology

- Habitability of planetary surfaces exposed to ionizing radiation
- Space colonization
  - [not discussed here]
- Transportation of life in space
  - Panspermia theories [not discussed here]



Extremophiles: conclusions

- For a correct interpretation of the properties of extremophiles in astrobiological context it is crucial to understand whether they represent ancient forms of life that have survived in isolated environmental niches, or forms of life that have adapted to special conditions in the course of evolution
- Both factors can be at work, but the implications are different

2. Habitable astronomical environments

As in the case of the Earth, one can think of several criteria of habitability

Here we focus on:

– temperature and pressure limits of the environment

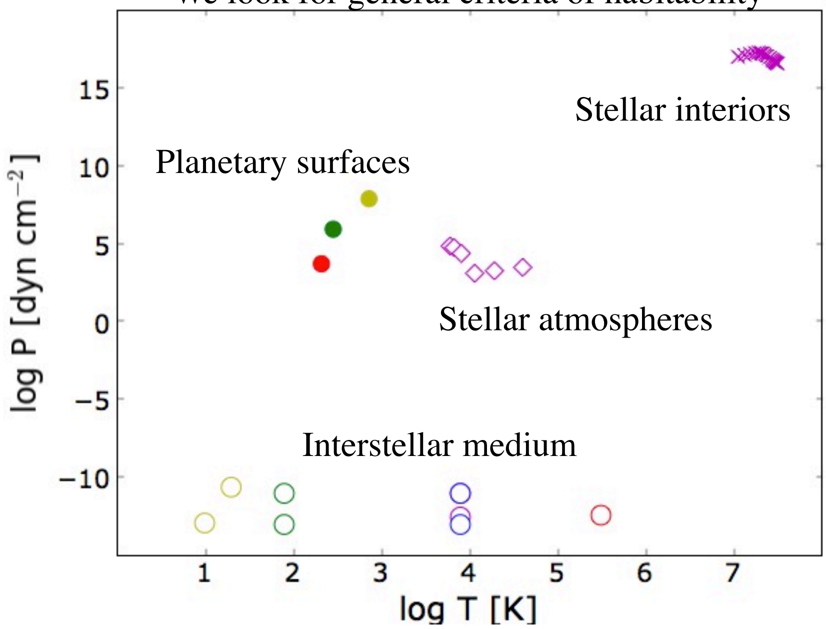
We introduce a general criterion of habitability, based on the survival of chemical bonds of biological interest, valid for any form of chemical life

The application of this criterion demonstrates the unicity of planets and their moons as potential habitable environments

The habitabile universe

Astronomical environments in the temperature-pressure (*T*-*p*) diagram

We look for general criteria of habitability



Habitability and energies of chemical bonds

- We may obtain an operational definition of habitable environment by comparing:
  - –the mean kinetic energy $E_{kin}=(3/2)kT$
  - –with the characteristic energy of chemical bonds of biological molecules

    To prevent the distruction of biological molecules it should be:

    $E_{kin} < E_{bonds}$
- Typical energies of chemical bonds:
  - –Covalent bonds

    between ~50 e ~200 kcal/mole

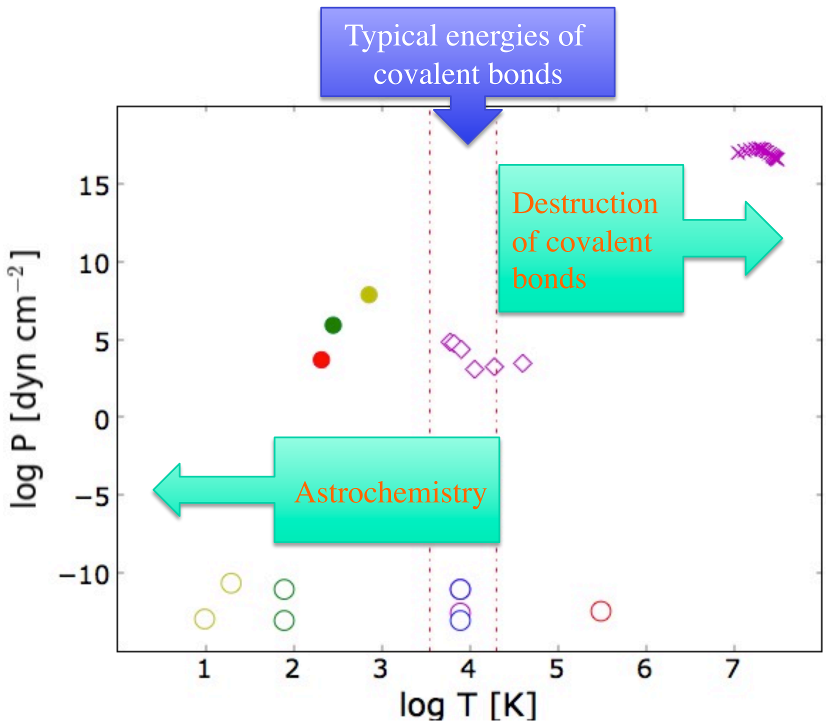
    → 100 kcal/mole ~ 418 kJ/mole ~ 4.2 eV
  - –Hydrogen bonds

    between ~1 e ~10 kcal/mole

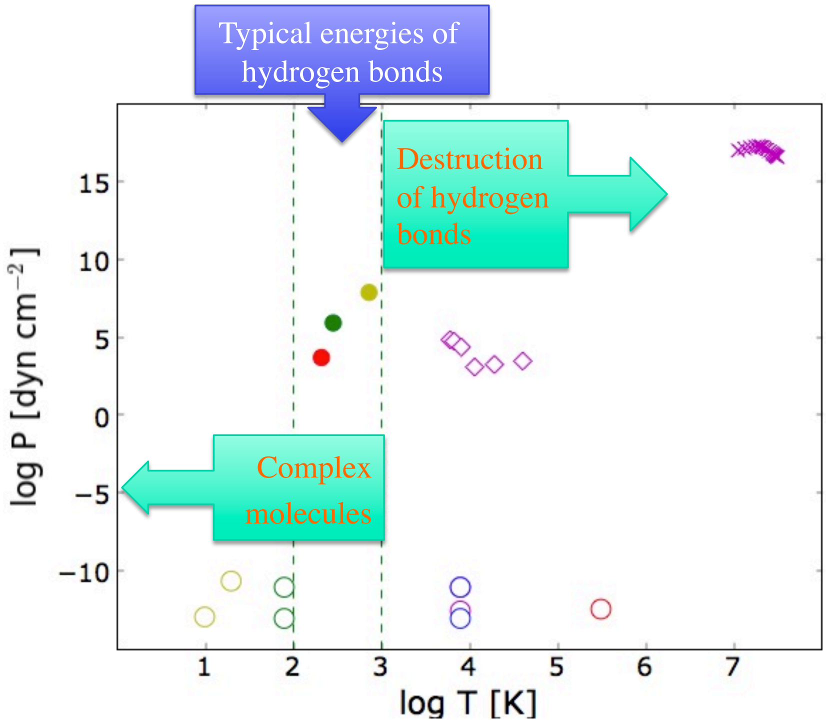
    → 5 kcal/mole ~ 20 kJ/mole ~ 0.2 eV

We now convert in temperature units these energies in order to set limits of habitability in the diagram *T-p*

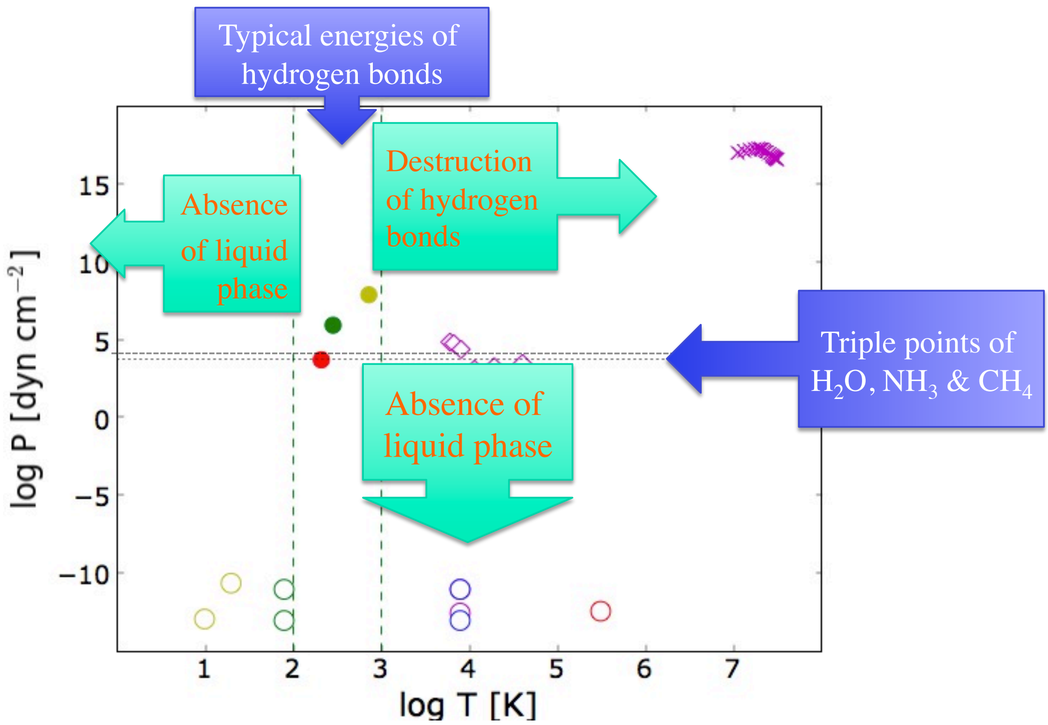
The habitable universe



The habitable universe



The habitable universe



The habitable universe

- Conclusion

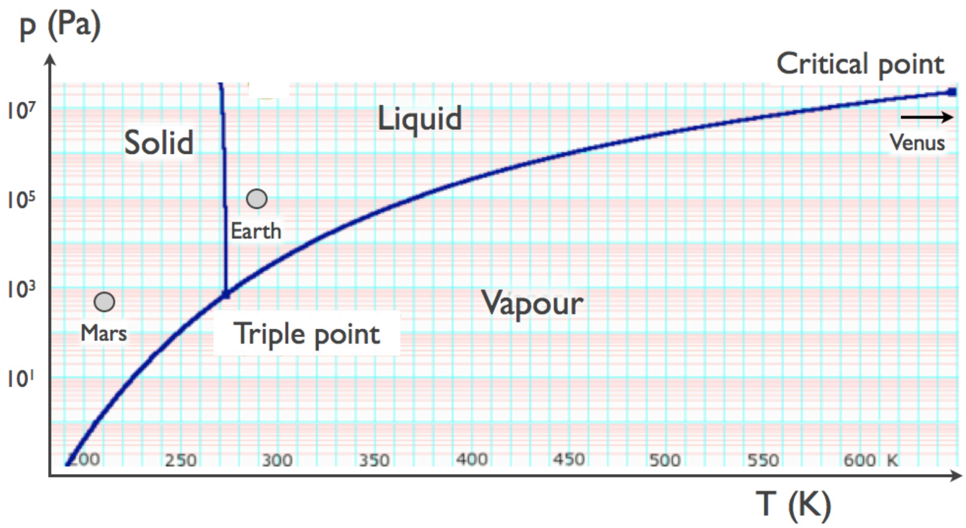
  Planetary systems are the only possible habitable environments in the universe, based on the "hydrogen bond criterion"

  – The fact that different types of planets and moons can be located in a range of distances from their central stars, offers a variety of local climates among which we can search for habitable environments

The habitable universe

The "liquid water criterion" is a special case of the "hydrogen bond criterion" of habitability, because the intermolecular forces of water are hydrogen bonds

The "liquid water criterion" is less universal than the "hydrogen bond criterion" but, on the other hand, is very well defined from the point of view of the thermodynamical variables (T, p)

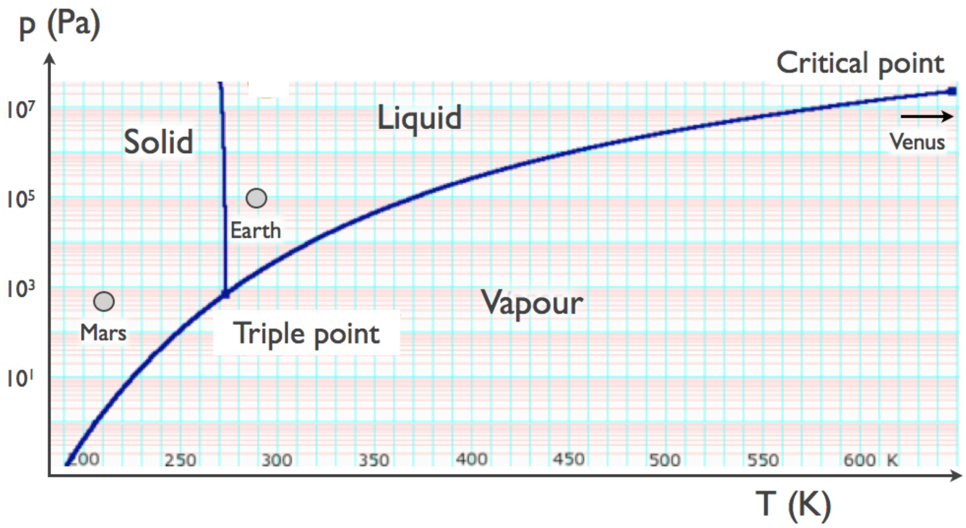


Planetary habitability

Energy balance climate model → Planet surface temperature
→ Liquid water criterion → Planet surface habitability

Minimum surface pressure for habitability

$$p_s > 611 \text{ Pa}$$



Quantifying the habitability with the liquid water criterion

The climate simulation yields
the surface temperature
as a function of latitude and time

$$T(\phi, t)$$

Habitability function

$$H(\phi, t) = \begin{cases} 1 & \text{if } T_{\text{melt}}(p) \le T(\phi, t) \le T_{\text{boil}}(p) \\ 0 & \text{otherwise} \end{cases}$$

Liquid water criterion

Mean global annual habitability

$$h = \frac{\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} d\phi \int_0^P dt \, [H(\phi, t) \, \cos\phi]}{2P}$$

zero-order, global planetary Energy Balance

$$I = S(1 - A)$$

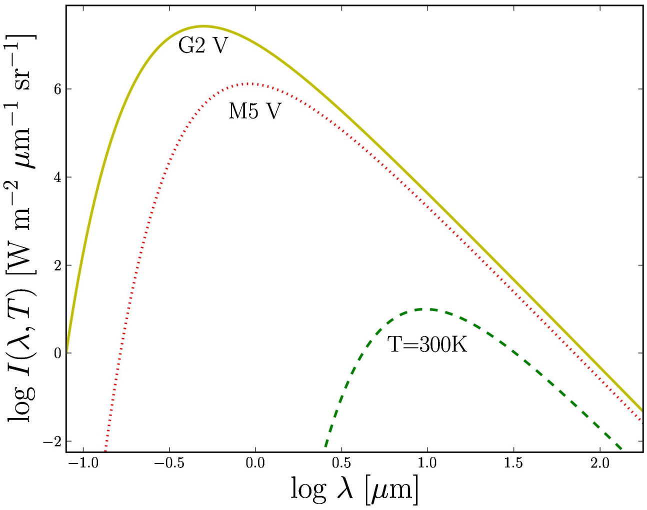
OUTGOING PLANETARY RADIATION (thermal IR)

PLANETARY ALBEDO

INCOMING STELLAR RADIATION (visible/UV)

Spectral distributions of the incoming stellar radiation, S, and of the outgoing planetary radiation, I

Given the different spectral distributions, these two terms of the planetary energy balance can be treated separately



Planetary albedo

- Albedo
  - Depends on the type of surface
    - Examples:

      A(ice) ~ 0.5/0.6

      A(snow) ~ 0.8/0.9

      A(sand) ~ 0.25
  - Each type of surface has its own wavelength dependence

Planet	Albedo in the visible
Mercury	0.11
Venus	0.65
Earth	0.38
Mars	0.15
Jupiter	0.52
Moon	0.12

Allen (2000)

Planet effective temperature

From the energy equilibrium equation, assuming black body emission

$$4 \pi R^2 \sigma T^4_{eff} = \pi R^2 S (1-A)$$

where

S: "solar costant"

stellar flux received by the planet

A: planetary albedo

fraction of stellar radiation reflected back into space

$$\sigma T^4_{eff} = \frac{1}{4} S (1-A)$$

Comparison between observed mean surface temperature and effective temperature in rocky planets of the Solar System

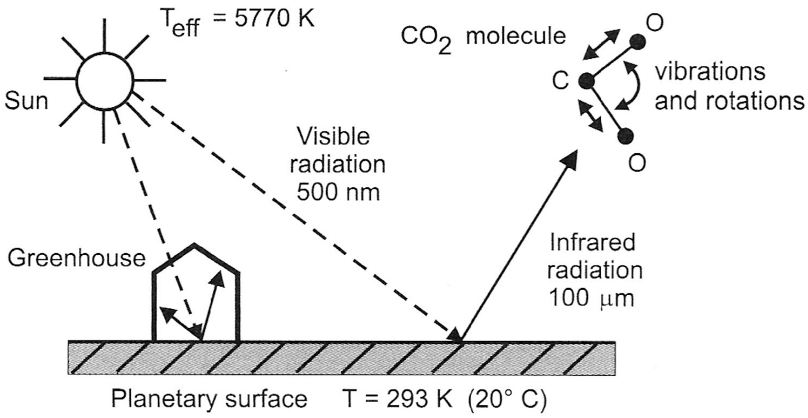
Planet	Mean surface temperature [K]	T_{eff} [K]
Venus	730	230
Earth	288	255
Mars	210	212

Differences are due to the greenhouse effect

In the case of Earth there is a difference of +33 K

In the case of Venus there is a clear discrepancy, due to the presence of thick CO_2 atmosphere

In the case of Mars, which has a very tenuous atmosphere, there is a good agreement



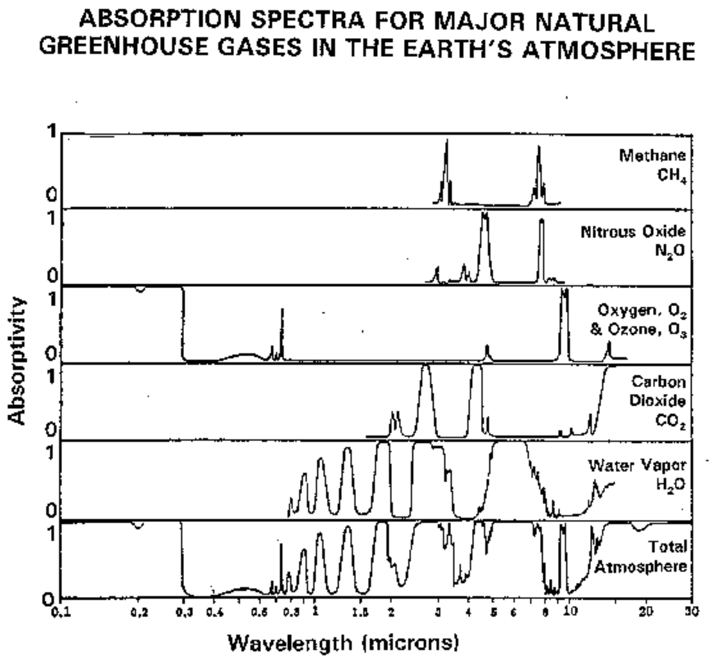
As a result of the greenhouse effect, the thermal radiation is trapped in the atmosphere and the surface temperature rises

We can quantify the greenhouse effect by comparing the effective temperature expected for the given stellar radiation, with the measured surface temperature:

$$T_s = T_{eff} + \Delta T(\text{greenhouse})$$

In the case of the Earth:

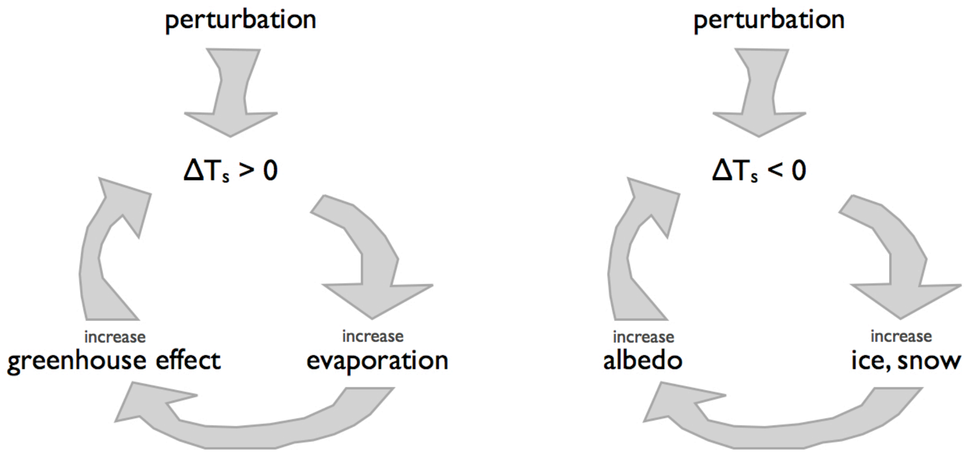
$$\Delta T = +33\ \text{K}$$



[After J. N. Howard, 1959: *Proc. I.R.E. 47*, 1459; and R. M. Goody and G. D. Robinson, 1951: *Quart. J. Roy. Meteorol. Soc. 77*, 153]

Climate instabilities

can drive the planet temperature out of the range of habitability



Mechanism of climate stabilization

We know that the Earth's climate has been relatively stable in the course of geological time scales

This fact is somewhat surprising in light of the long term changes that have occurred in terms of solar radiation, Earth's atmospheric composition and other factors

The long term stability of the Earth's climate suggests the existence of a mechanism of climate stabilization

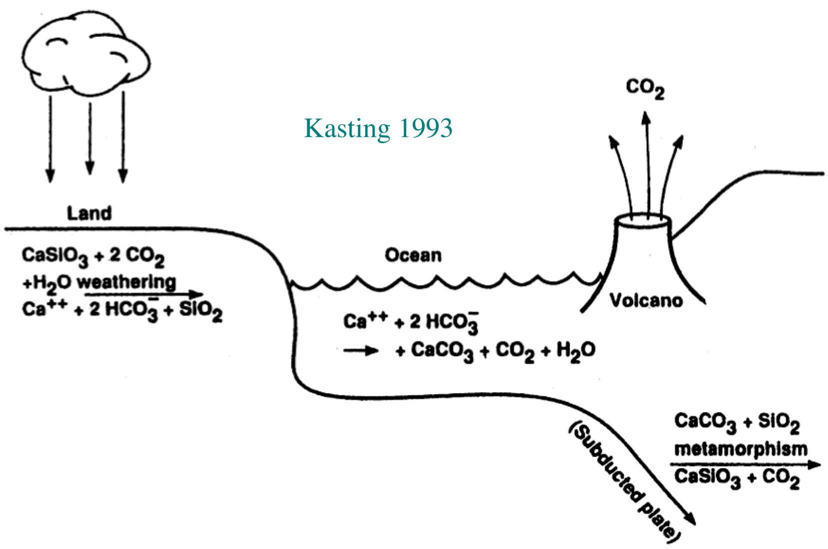
The mechanism invoked for the Earth is based on a CO_2 inorganic cycle

Its is instructive to consider this mechanism since, in principle, it could be at work also in other planets

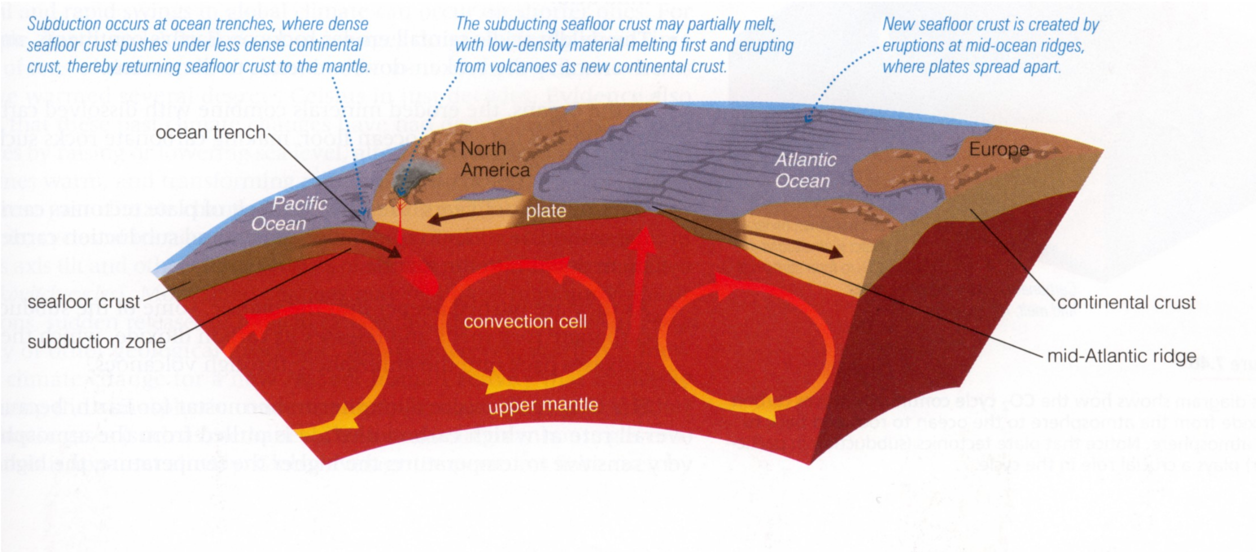
The CO_2 cycle of climate stabilization

- Main steps
  (1) Weathering processes remove CO_2 from the atmosphere; the chemical products are gradually deposited to the bottom of the oceans and eventually subducted, due to tectonic activity
  The weathering efficiency increases with atmospheric temperature
  (2) CO_2 from the Earth's mantle is emitted to the atmosphere by means of volcanic activity
  The rate of CO_2 emission is independent of the atmospheric temperature
- The time scale of the cycle is estimated to be in the order of ~ 5 x 10^5 years
  – The existence of a convective mantle, tectonic motions and volcanic activity play a key role for this mechanism to work

The CO_2 cycle of climate stabilization



- Conclusion: the existence of tectonics and volcanism may play an important role in planetary habitability
  - In the present-day Solar System, only the Earth features these types of geophysical activities



Circumstellar habitable zone

$$\sigma T^4_{eff} = \frac{1}{4} \; S \; (1-A)$$

$$S = L_* / (4\pi \, d^2)$$

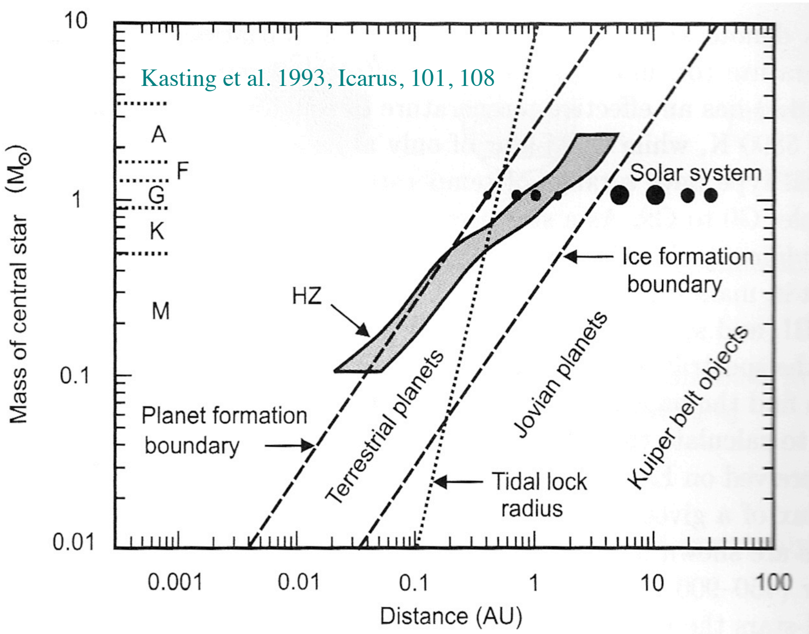
For a given type of planet, there will be an annulus of distances from the star where the surface temperature is suitable for water to be in the liquid phase

This liquid water interval of distances is called the circumstellar habitable zone

Its extension will depend not only on the stellar flux, but also on the planetary properties, and in particular on the strength of the greenhouse effect

Circumstellar habitable zone

- Calculated for stars of different spectral types
  - Different types of criteria are adopted to define the inner and outer edge



The inner edge of the habitable zone

- If the planet temperature is too high and water is present on the planet, a runaway greenhouse mechanism may take place
  - At high temperatures, the partial pressure of water vapour increases in the atmosphere, leading to a strong greenhouse effect that rises the temperature even more
  - In extreme cases, the vapour may reach the outer levels of the planet atmosphere, where the water molecules can be dissociated by high energy stellar photons
  - The hydrogen produced by photodissociation can be lost to space
  - All together, this catastrophic event may lead to the disappearence of liquid water on the planet
  - This mechanism is used to define the inner edge of the habitable zone

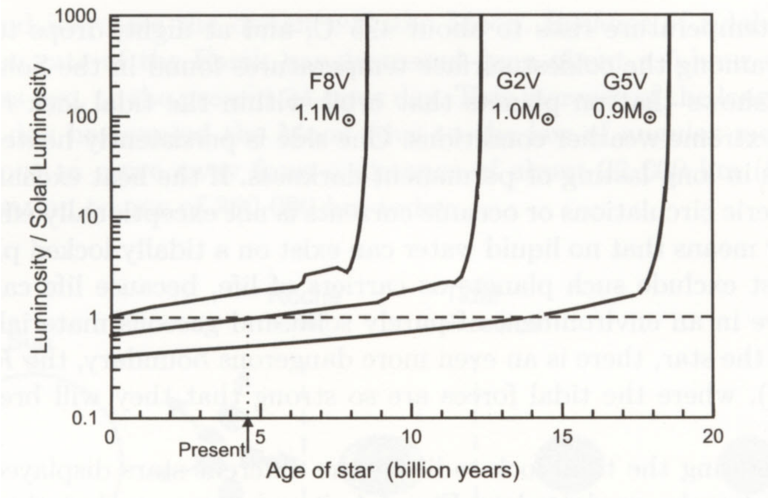
The outer edge of the habitable zone

- An increase of greenhouse gases in the planetary atmosphere makes the planet habitable at lower levels of stellar flux, i.e. at larger distances from the central star

- The outer edge of the habitable zone is commonly defined assuming that the planetary atmosphere is rich in greenhouse gases
  – Typically an atmosphere dominated by CO_2, as in the case of Mars

Shift of the circumstellar habitable zone

- The evolution of the stellar luminosity shifts the location of the circumstellar habitable zone inside planetary systems
  –The shift is gradual during the main sequence stage of hydrogen burning, but is sudden at later stages of stellar evolution



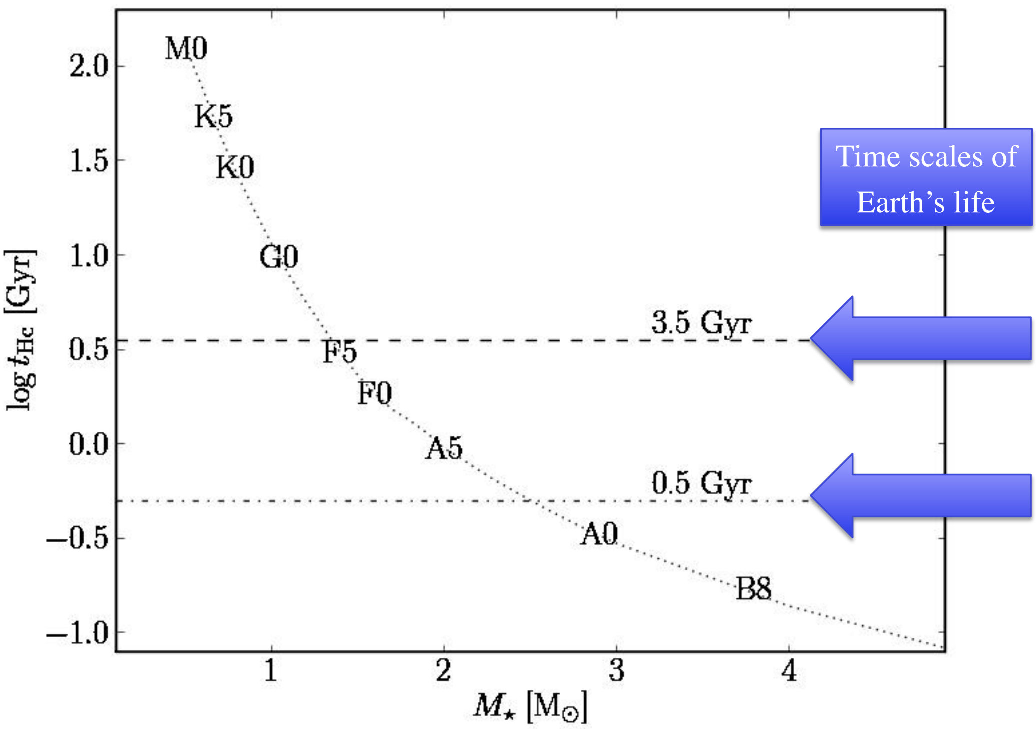
Continuous circumstellar habitability

- The gradual shift of the habitable zone during the hydrogen-burning phase set constrains on the circumstellar habitable zone suitable for advanced forms of life
  - The zone must be continuosly habitable since life evolution may take a few billon years to produce advanced forms of life, as in the case of the Earth
  - Mechanisms of climate stabilization are important in this respect
- The sudden shift of the habitable zone after the hydrogen burning phase contrains the type of stars that are of astrobiological interest

  example:

  $t(H_{burning}) \geq 10^9$ yr → M(star) ≤ 2 M(sun) & spectral type ≥ A5

Time spent on the main sequence by stars with different spectral types



Continuous habitability and orbital stability

- In order to have continuous habitability, the planetary orbit must be dynamically stable in the long term (~10^9 yr)
  - –Episodes of dynamical instability are likely to be present in the early stages after the formation of planetary systems

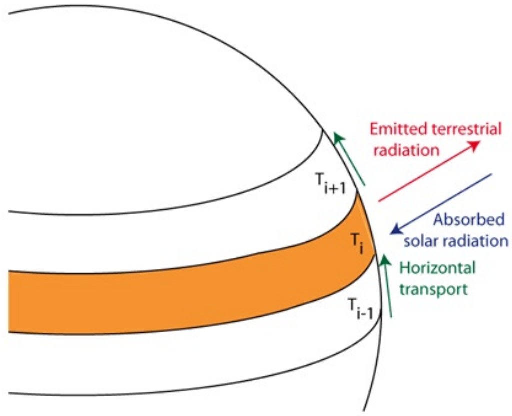
- The dynamical stability of planetary systems can be studied only with methods of numerical integration (N-body problem)
-
- Dynamical stability, once applied only to the Solar System, starts to be applied to extrasolar planetary systems
  - –Examples
  - –Dynamical stability of orbital parameters deduced by observational methods, which need to be tested
  - –Exploration of orbital parameter space were planets not detected by observations may exist in stable orbits

Surface habitability and climatology

- Physics of the atmosphere and climate models, originally developed for Earth studies, are becoming a key tool for predicting the habitability of extrasolar planets

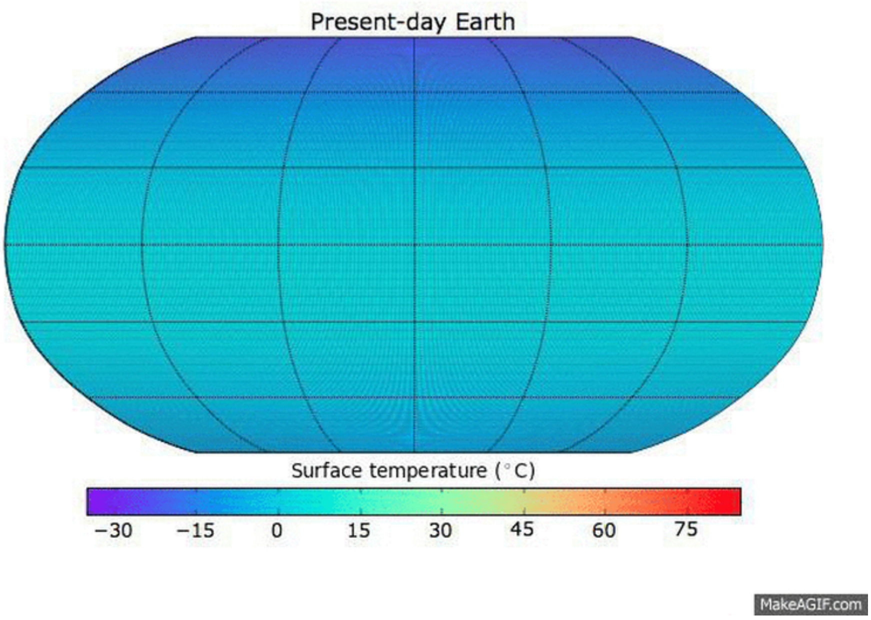
- A large of variety of climate models exist
  - The state-of-the-art Earth model are called "Global Circulation Models" (GCM)
  - Extremely detailed and time-consuming in term of computational resources
  - For exploring the habitability of extrasolar planets we consider "Energy Balance Models" (EBM)

Energy balance models (EBM) of planetary climate

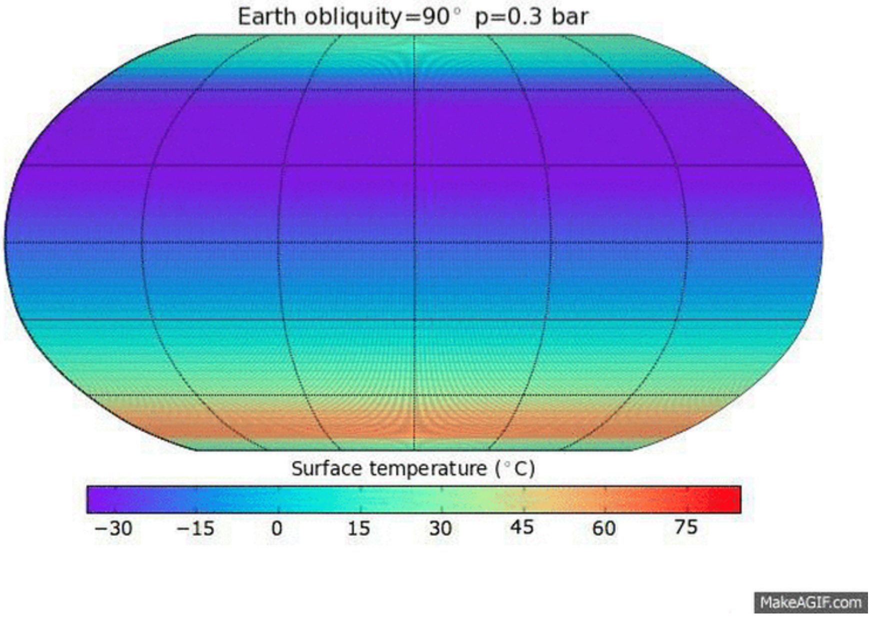


$$I_i + C_i \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left[D_i\left(1 - x^2\right)\frac{\partial T}{\partial x}\right] = S_i\left(1 - A_i\right)$$

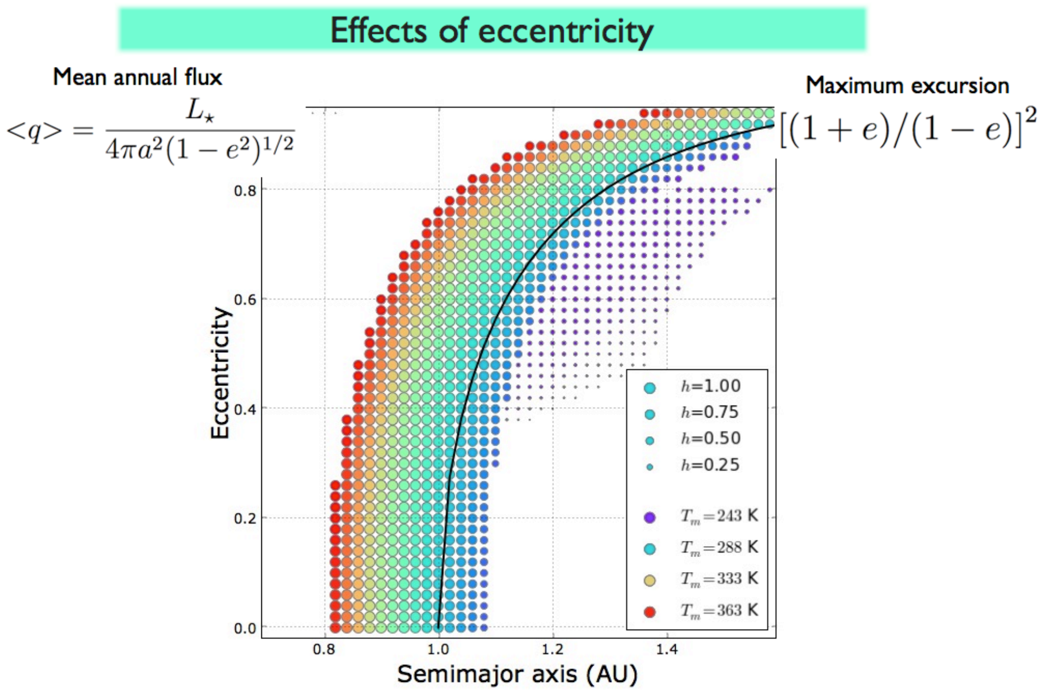
Examples of application of climate EBM
Seasonal and latitudinal surface temperature of the Earth



Examples of application of climate EBM
Seasonal and latitudinal surface temperature of an Earth-like planet with very high axis obliquity and low atmospheric pressure



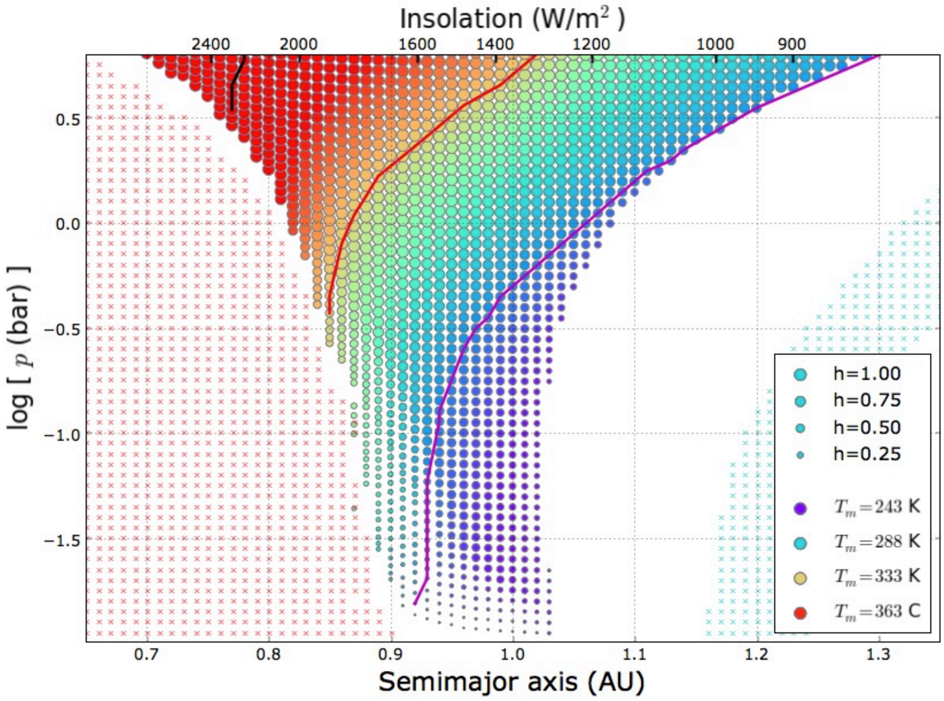
Examples of application of climate EBM



Pressure dependence of the habitable zone

Obtained running a large number of climate simulations

Vladilo et al. (2013)



Habitability under the planet surface

- The definition of habitable zone relies on the concept of surface habitability
  - Habitability under the planet surface could be present in planetary bodies outside the circumstellar habitable zone, in particular beyond the outer edge
- Temperature and pressure gradients may yield conditions of habitability in the interior of planets or satellites
  - Internals sources of heat yield a temperature gradient in the planet interior

    Europa is a good example of this possibility
  - The pressure gradient towards the planetary interior may improve the conditions of habitability

    Mars is an excellent example of this possibility