

Physico-chemical requirements of planetary habitability

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- **Habitability of the Earth**

- The Earth is the only reference that we have to test the concept of habitability
- The broad range of physical and chemical conditions that are found on Earth (surface at different latitudes and altitudes, deep Earth, seas, deep oceans, etc.) can be used to explore the limits of natural environments in which life can exist

- **Broadening the concept of habitability**

- In the last decades, the resistance/adaptation of life has started to be tested also in artificial space environments in the Solar System, such as the International Space Station
- The concept of habitability needs to be adapted also to include extrasolar planetary systems as well as non-terrestrial forms of life

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Habitability

The habitability can be defined as the capability of an environment to host life

- The definition of habitability is related to the definition of life

Habitability in astrobiological context

- One of the goals of astrobiology is to study the distribution of life in the Universe
- Studies of habitability provide a way of understanding which astronomical environments are potentially suitable for hosting life
- The requirements of habitability can be investigated more easily, even with remote observations, than the effective presence of life

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Habitability criteria

The physico-chemical requirements of terrestrial life are the starting point to define possible criteria of habitability

- Ideally, one should try to adapt the criteria to other possible forms of life

One can think of several criteria:

- Presence of energy sources, presence of chemical elements of biological interest, temperature limits, limits of ionizing radiation, limits of salinity, etc...

The most commonly adopted definition is based on the liquid water criterion

- Water should be present in the environment and the thermodynamical conditions should allow water to be in the liquid phase
- The liquid water criterion can be thought as a special case of the “hydrogen bond” criterion, that we now discuss

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The hydrogen bond criterion of habitability

- The “hydrogen bond” criterion is a general criterion of habitability, not specific to terrestrial life
- The criterion is valid for any form of chemical life where hydrogen bonds play an essential role
 - Hard to imagine any form of chemical life without hydrogen 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

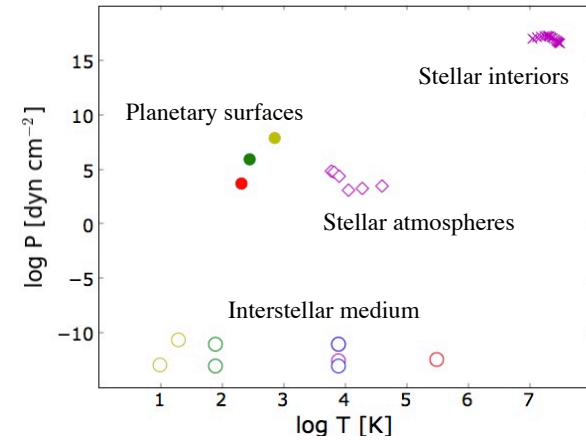
To prevent the destruction of biological molecules it should be:

$$E_{kin} < E_{chemical\ bonds}$$

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

We investigate the survival of different types of chemical bonds



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Habitability and energies of chemical bonds

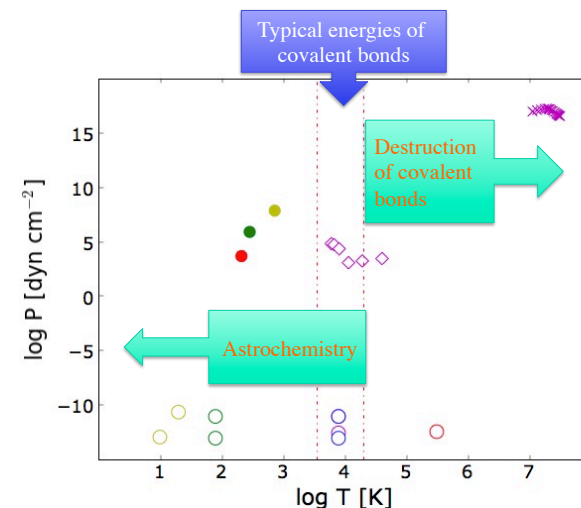
- Typical energies of chemical bonds:
 - Covalent bonds
 - between ~ 50 e ~ 200 kcal/mole
 - $\rightarrow 100$ kcal/mole ~ 418 kJ/mole ~ 4.2 eV
 - Hydrogen bonds
 - between ~ 1 e ~ 10 kcal/mole
 - $\rightarrow 5$ kcal/mole ~ 20 kJ/mole ~ 0.2 eV

We consider different types of astronomical environments with characteristic values of temperature, T , and pressure, p

We convert in temperature units the above energies in order to set limits for the survival of chemical bonds in the diagram T - p

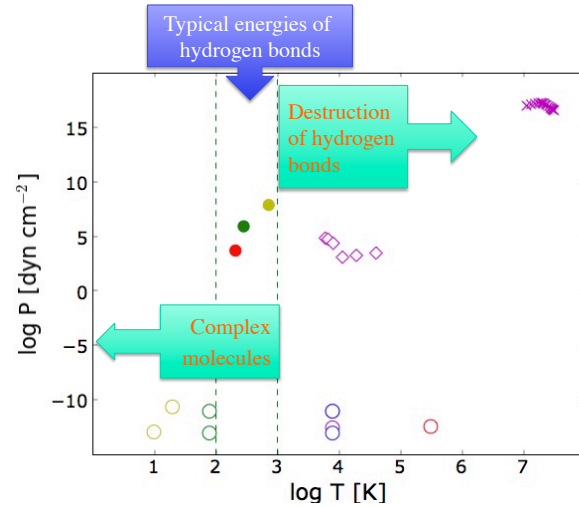
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Survival of covalent bonds



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Survival of hydrogen bonds



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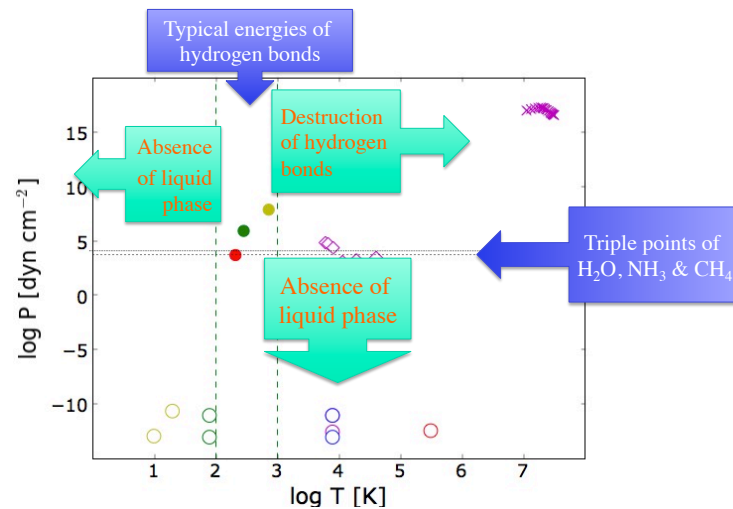
Conclusion:

based on the “hydrogen bond criterion”, planetary systems provide the only possible habitable environments in the universe

- 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
- However, it is difficult to set clearcut energy thresholds using the hydrogen bonds: as a result, this criterion is more from a conceptual point of view than from a practical point of view
- The “liquid water criterion” is a special case of the “hydrogen bond criterion”, because the intermolecular forces of water are hydrogen bonds
- The “liquid water criterion” is well defined from the point of view of the thermodynamical variables (T, p)

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The habitable universe according to the hydrogen bond criterion



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Habitability of different types of planetary environments

Surface habitability

- The conditions of habitability are commonly referred to the possibility of hosting life at the surface of the planet or moon
- Surface habitability is of special interest since surface life has a great potential for producing chemical signatures in the planet atmosphere which could be detected with remote spectroscopy

Sub-surface habitability

- Based on the example of the Earth, life can also be present below the surface, not only in the oceans, but even at the bottom of the oceans or at great depths in the continents
- In other planets or moons, such as Europa, life could be present below a surface layer of ice

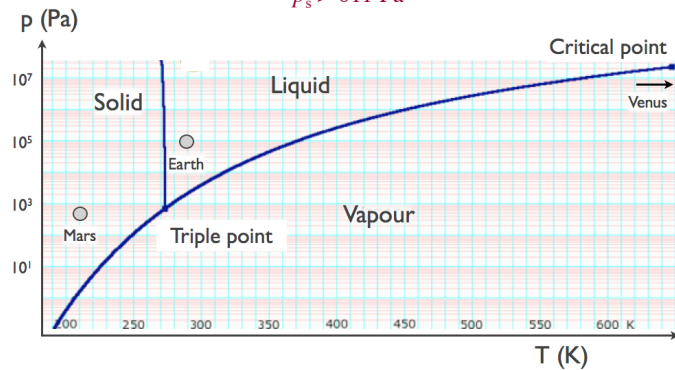
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The liquid water criterion constrains the ambient temperature and pressure

On the Earth's surface ($p_s = 1 \text{ bar}$) $0^\circ\text{C} \leq T \leq 100^\circ\text{C}$

In other planets, the criterion sets the minimum value of ambient pressure:

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



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Carbon, energy sources and habitability

The existence of energy sources is an essential requirement of any habitable environment

Living organisms require energy to carry out their metabolism

A source of carbon is also required

The synthesis of biomolecules requires carbon to be fixed in organic form (e.g. carbohydrates); inorganic carbon (e.g. CO_2) cannot be directly used

Organisms can be classified according to the way they acquire energy and carbon

Autotrophs acquire energy and carbon directly from the abiotic world

Energy is obtained from reduction-oxidation (redox) reactions or from stellar photons

Inorganic carbon is autonomously “fixed” in organic form

Heterotrophs acquire energy and carbon from pre-existing organic molecules

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Planetary atmospheres and habitability

- The presence of a planetary atmosphere is an essential requirement of habitability
 - Minimum atmospheric pressure at the planet surface is set by the liquid water criterion
 - The chemical processes in the atmosphere can lead to the formation of molecules essential for life processes
 - Such processes are influenced by the stellar radiation field and other radiation components of the interplanetary medium
- Life, if present, will in turn affect the chemical composition of the atmosphere

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Carbon and habitability

Carbon is cosmically abundant and, apparently, does not set a severe constraint of habitability

The example of the Solar System shows that the abundance of carbon in rocky planets can be relatively low

Even so, it is sufficient to maintain a large biosphere, such as the terrestrial one

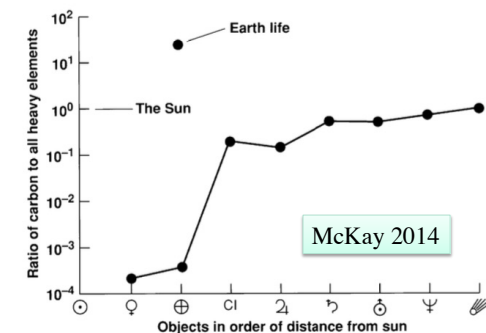


Fig. 1. Carbon in the Solar System as ratio by number to total heavy elements (>He) for various Solar System objects. Carbon is depleted in the inner Solar System. The x axis is not a true distance scale but the objects are ordered by increasing distance from the Sun. Data are from the following compilations: comets and Type I carbonaceous chondrites, CI (72); life (73); Earth and Venus (74); Sun, Jupiter, Saturn, Uranus, and Neptune (75). Mars is not shown because the size of its carbon reservoir is unknown. Figure from ref. 76.

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Energy sources and habitability

- Any habitable environment must provide energy sources to the autotrophs
 - Heterotrophs use the energy and organic carbon fixed by autotrophs (the very first heterotrophs might have used the organics present in the environment)
- Terrestrial autotrophs acquire energy in two ways:
 - chemiothrophs use redox reactions (oxidizing-reducing reactions)
 - photothrophs use stellar photons
- We now show examples of reaction schemes
 - Reaction schemes summarize the total input and output budget of a network of reactions

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Energy sources for terrestrial autotrophs: oxidation-reduction reactions

- Metabolism based on sulphur
 - Example of reaction scheme:
 $6 \text{CO}_2 + 12 \text{H}_2\text{S} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{H}_2\text{O} + 12 \text{S} + \text{energy}$
 - Also this scheme produces energy while fixing organic carbon
 - Probably very ancient
 - Examples of microorganisms:
Thiobacillus thiooxidans, *Sulfolobus acidocaldarius*
 - Example of habitat: sulphuric caves

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Energy sources for terrestrial autotrophs: oxidation-reduction reactions

- There are many different types of oxidation-reduction reactions
 - Adapted to the chemicals that are available in specific environments
- Examples
 - Methanogenesis & sulfur-based metabolism
- Methanogenesis
 - Oxidation-reduction reactions in which hydrogen is oxidized while carbon dioxide is reduced
 - Example of reaction scheme:
 $4 \text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O} + \text{energy}$
 - Provides energy while fixing the carbon that becomes available for further synthesis of organic molecules
 - Employed, for instance, by autotrophs in the deep ocean “hydrothermal vents”

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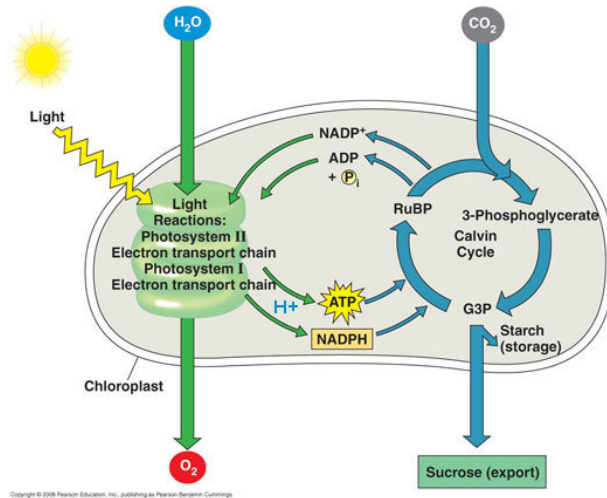
Energy sources for terrestrial life: photosynthesis

- Photosynthesis converts stellar photons into chemical energy
- Extremely complex cycle of chemical reactions involving many proteins and small molecules
- Takes places in different steps; only the first reactions of the cycle are triggered by light; most of the reactions are light-independent
- There are different types of photosynthesis (e.g., non-oxygenic and oxygenic)
- Oxygenic photosynthesis is the most diffuse in present-time terrestrial life
- It is the main sources of organic carbon and oxygen used by aerobic organisms
- The overall budget of reactants and products in the oxygenic photosynthesis can be expressed in the idealized scheme of reaction
- $$\text{CO}_2 + \text{H}_2\text{O} + h\nu \rightarrow (\text{CH}_2\text{O}) + \text{O}_2$$
- (CH₂O) represents a carbohydrate (carbon fixation)
- Energy is stored by converting ADP to ATP

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Oxygenic photosynthesis

Complex network of chemical reactions, part in light and part in dark



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Water and habitability

- Water molecules are built up with cosmically abundant elements
 - As in the case of carbon, the example of the Solar System shows that water may have a relatively low abundance in rocky planets
- Life on Earth is found in relatively dry environments
 - In rocks in dry deserts, in Antarctica
 - These examples show that a small amount of rain, fog, or snow and even atmospheric humidity can be adequate for photosynthetic production producing a microbial community
- As a long as a small amount of water is present on the planet, the minimum requirement of habitability is satisfied

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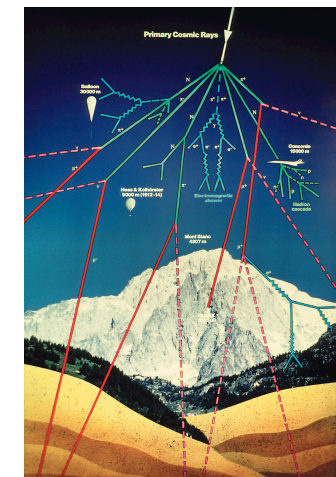
Energy and habitability

- Energy for life can come from chemical redox couples generated by geothermal processes or light from the central star
- Geothermal flux can arise from (i) the planet cooling off from its gravitational heat of formation, (ii) decay of long-lived radioactive elements, or (iii) tidal heating for a close-orbiting world or moon
 - On Earth only a tiny fraction of the geothermal heat is converted into chemical energy, whereas about half the solar flux occurs at wavelengths that are usable for photosynthesis
- Minimum requirements for photosynthesis
 - Based on the example of the Earth, we know that photosynthesis can take place also at very low levels of stellar insolation
 - A fraction $\sim 5 \times 10^{-6}$ of the direct solar flux at Earth is sufficient
 - Even at the orbit of Pluto, light levels exceed this value by a factor of ~ 100
 - Laboratory tests indicate that photosynthesis can work efficiently also changing the spectrum of the star (i.e., with late-type stars)

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Ionizing radiation and habitability

- Ionizing photons and particles are called “ionizing radiation”
- The Earth is exposed to different types of ionizing radiation
- Ultraviolet radiation
 - Originated in the Sun and 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



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Protective effect of the Earth atmosphere

- **Ultraviolet photons**

- The ozone (O₃) 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 O₃ is due to the photodissociation of O₂ in the high atmospheric layers, followed by the interaction of the O radicals with undissociated O₂ 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 that can reach the planet surface

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Radiation dose and life

- **Equivalent dose**

- It is defined in terms of the absorbed dose multiplied by a weighting factor which depends on the type of radiation:

$$H = \sum_R w_R D_R$$

The SI unit is the sievert: 1 Sv = 1 J/kg

Type of radiation, R	Energy range	Quality or weighting factor, w _R
Photons, electrons	All energies	1
Neutrons	< 10 keV	5
	10–100 keV	10
	100 keV–2 MeV	20
	2–20 MeV	10
	> 20 MeV	5
Protons	< 20 MeV	5
Alpha particles, fission fragments, heavy nuclei		20

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Radiation dose and life

- **Absorbed dose**

- Amount of ionizing radiation absorbed per unit mass of material (e.g., a tissue or organ)

The SI unit is the gray: 1 Gy = 1 J/kg

- Biological effects depend not only on the total dose but also on the rate at which this dose is received (e.g. mGy/yr)

- **Type of radiation**

- The biological effect also depends on the way in which the energy is deposited along the path of radiation, and this in turn depends on the type of radiation and its energy
- For the same absorbed dose the biological effect of α particles and neutrons, characterized by a high energy transfer, is higher than that of β or γ rays, with lower energy transfer

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Atmospheric columnar mass and surface dose of radiation

- **The surface dose of radiation scales with the atmospheric columnar mass**

- In hydrostatic equilibrium, the atmospheric columnar mass is given by $N_{\text{atm}} = p/g$ [kg/m²]

The radiation protection of the surface is linked to planetary properties that affect the habitability, such as the surface pressure and gravity

- Calculations of surface dose of radiation resulting from Galactic cosmic rays as a function of N_{atm} have been performed (e.g. Atri et al. 2013)

The results depend on the magnetic moment of the planet

TABLE 15. TOTAL BIOLOGICAL RADIATION DOSE IN mSV yr⁻¹

Magnetic moment (%)	100 g cm ⁻²	200 g cm ⁻²	500 g cm ⁻²	700 g cm ⁻²	1036 g cm ⁻²
0	553.33	262.51	17.22	3.02	0.65
15	509.81	260.48	18.20	3.38	0.46
50	257.21	141.20	11.98	2.53	0.42
100	171.46	97.04	8.70	1.84	0.34

A reference value for long-term resistance of human life is ~100 mSy/yr

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