Astrobiology
Lecture 7

Habitability

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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
- In remote astronomical bodies assessing the potential of habitability is easier than trying to detect life
- Studies of habitability can be used to select the most suitable targets for searches of biosignatures in exoplanets

- Habitability of the Earth
  - The Earth is the best reference that we have to test the limits of adaptation of life to extreme conditions
  - 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
- Habitability outside Earth
  - In the last decades, the resistence/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

Habitability of different types of planetary environments

Surface habitability

- The conditions of habitability commonly refer to the planetary surface
- Surface habitability is of special interest in exoplanets because surface life has the best chance of producing chemical signatures in the planet atmosphere which could be detected with remote spectroscopy

Sub-surface habitability

- The biosphere of the Earth shows that life can also be present below the surface, even at large depths in the or oceans
- In Solar System studies, sub-surface habitability has to be taken into account
- In planets or satellites, such as Mars or Europa, life could be present in lakes or oceans below the surface

Habitability criteria

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

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 criterion is the liquid water criterion

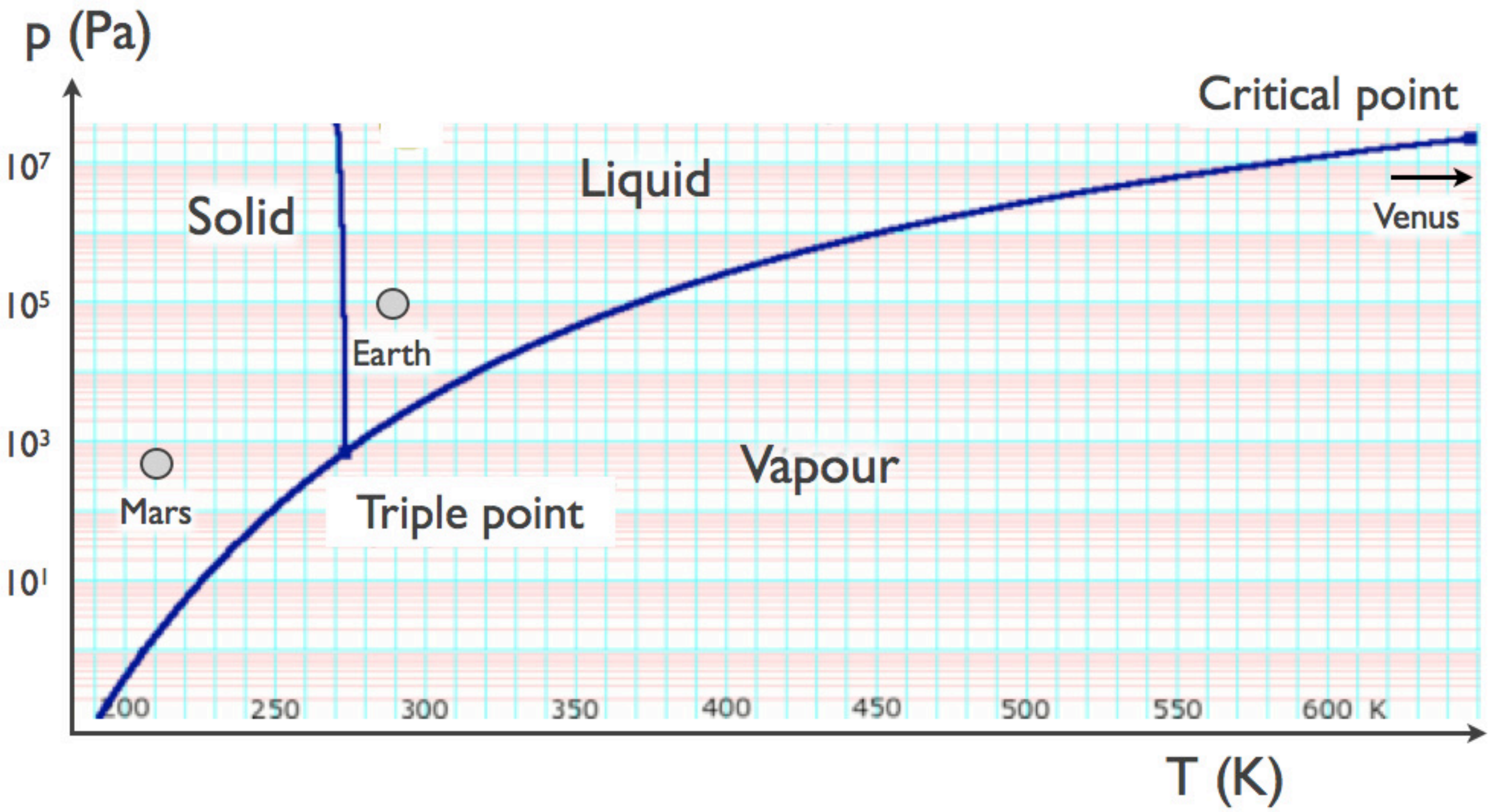
- Water should be present and the thermodynamical conditions of the environment should allow water to be in the liquid phase

The liquid water criterion constrains the ambient temperature and pressure

On the Earth's surface ($p_s = 1$ bar) $0\ ^oC \leq T \leq 100\ ^oC$

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

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



Water abundance and habitability

- Water is built up with cosmically abundant elements, but in planetary disks is abundant only in the outer regions
  - Some planets of the Solar System are dry
  - However, the lack of water reservoirs on a planet does not exclude the presence of life
- Life on Earth is found in relatively dry environments
  - In rocks in dry deserts, in Antarctica
  - A small amount of rain, fog, or snow and even atmospheric humidity can be adequate for the sustainance of a microbial community

- As a long as a small amount of water is present on the planet, a minimum requirement of habitability is satisfied

Carbon abundance and habitability

- Carbon is cosmically abundant and does not provides a severe contraint of habitability
- The example of the Solar System shows that the abundance of carbon in rocky planets, including the Earth, is low
  - Even so, it can be sufficient to maintain a large biosphere, such as the terrestrial one

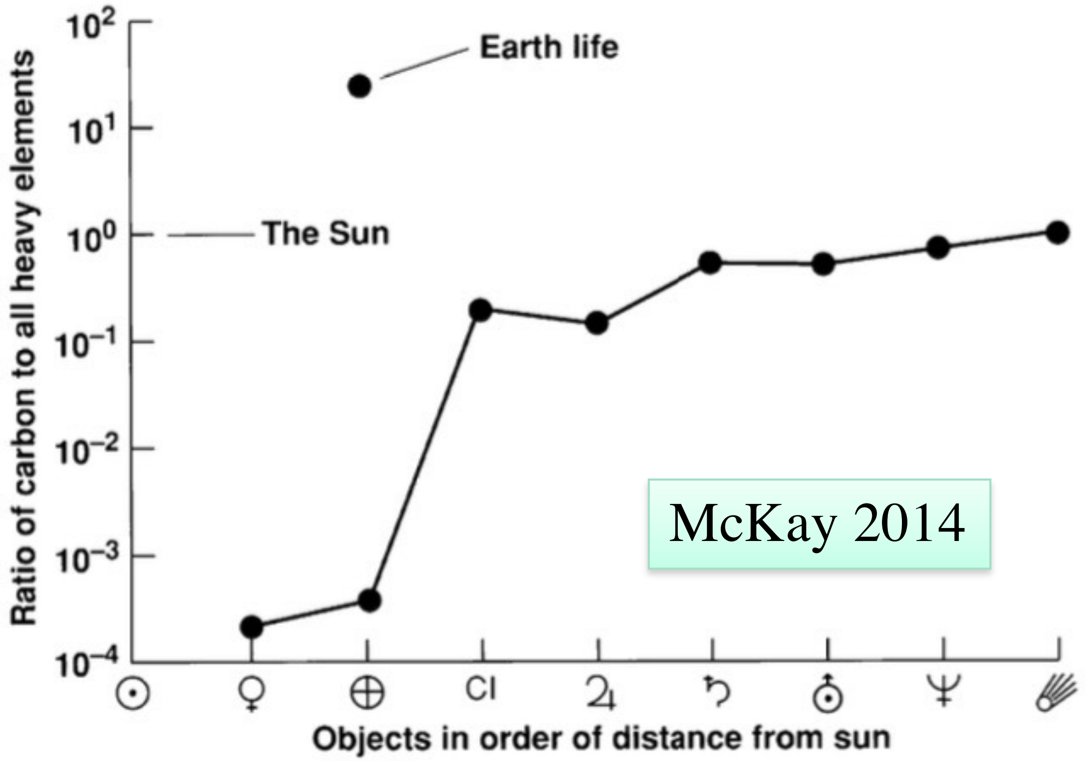


Fig. 1. Carbon in the Solar System as ratio by number to total heavy elements (>He) for various Solar System objects. Carbon is depleted in the inner Solar System. The *x* axis is not a true distance scale but the objects are ordered by increasing distance from the Sun. Data are from the following compilations: 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.

Energy sources, carbon fixation and habitability

The existence of energy sources is an essential requirement of habitability

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 adquire energy and carbon

<u>Autotrophs</u> adquire 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

<u>Heterotrophs</u> adquire energy and carbon from pre-existing organic molecules

Energy sources, carbon fixation and habitability

- Habitabile environment must provide energy sources to autotrophs
  - Heterotrophs use the energy and organic carbon fixed by autotrophs (if the first forms of life were heterotrophs, they should have used organics synthesized in prebiotic chemistry)

- Terrestrial autotrophs adquire 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
  - The complete network of reactions is much more complex than appears from the scheme

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

  Hydrogen is oxidized while carbon dioxide is reduced

  $4\,H_2 + CO_2 \rightarrow CH_4 + 2\,H_2O + \text{energy}$

  Provides energy while fixing organic carbon for metabolism

  Employed by autotrophs in oceanic “hydrothermal vents”

- Sulphur based metabolism

  Also this scheme produces energy while fixing organic carbon

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

  Probably very ancient, employed in sulphuric caves

  Examples: *Thiobacillus thiooxidans*, *Sulfolobus acidocaldarus*

Energy sources for terrestrial life: photosynthesis

Photosynthesis converts stellar photons into chemical energy

- Extremely complex cycle, involving many proteins and small molecules
- Only the first part of the cycle are triggered by light
- The remaining reactions are light-independent

Photosynthesis can be non-oxygenic (probably older) 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 can be expressed in the scheme:

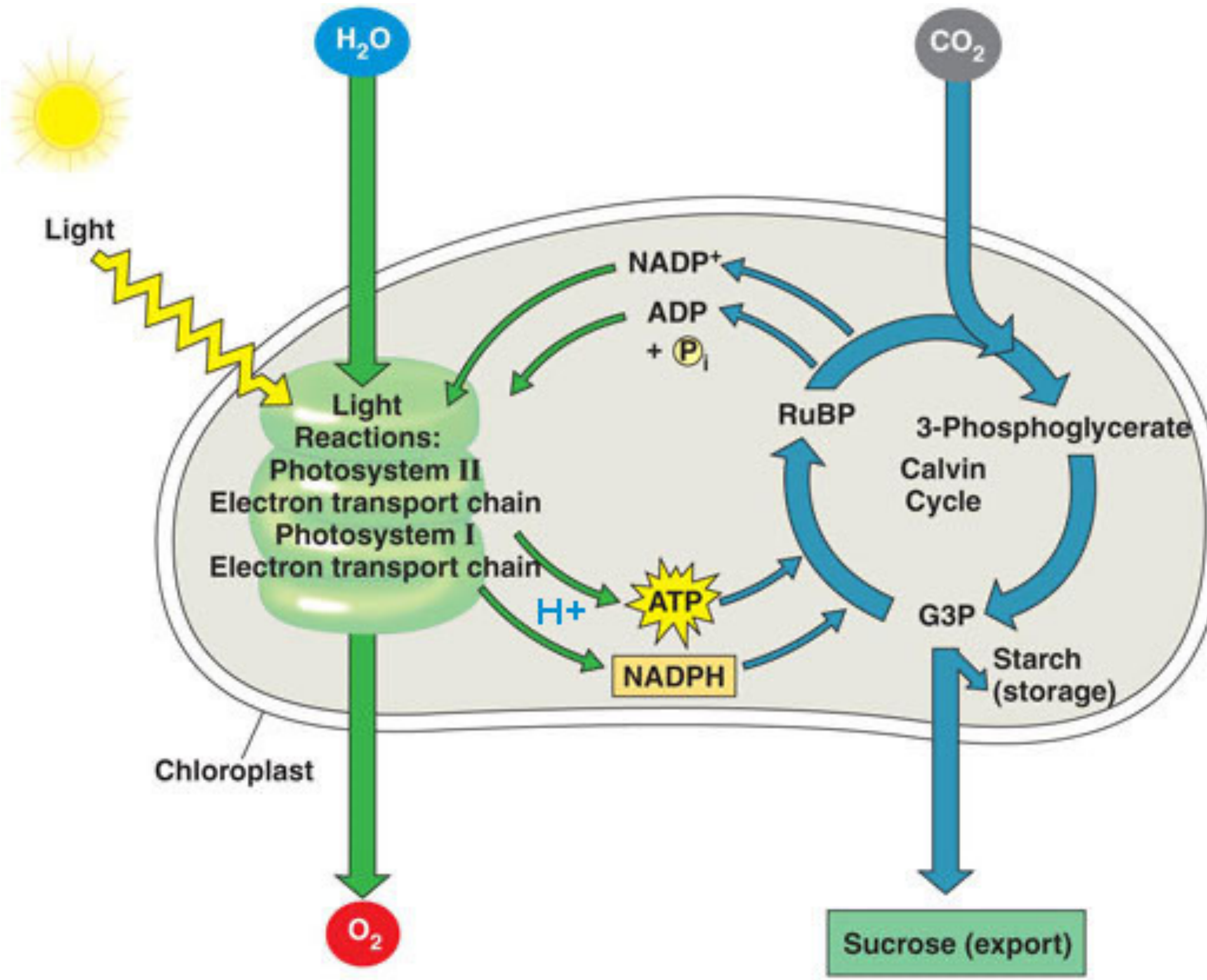
$$CO_2 + H_2O + h\nu \rightarrow (CH_2O) + O_2$$

- (CH_2O) represents a carbohydrate (carbon fixation)
- Energy is stored by converting ADP to ATP (not shown in the idealized scheme of reaction)

Oxygenic photosynthesis

Light reactions

Dark reactions



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)

Geothermal energy and habitability

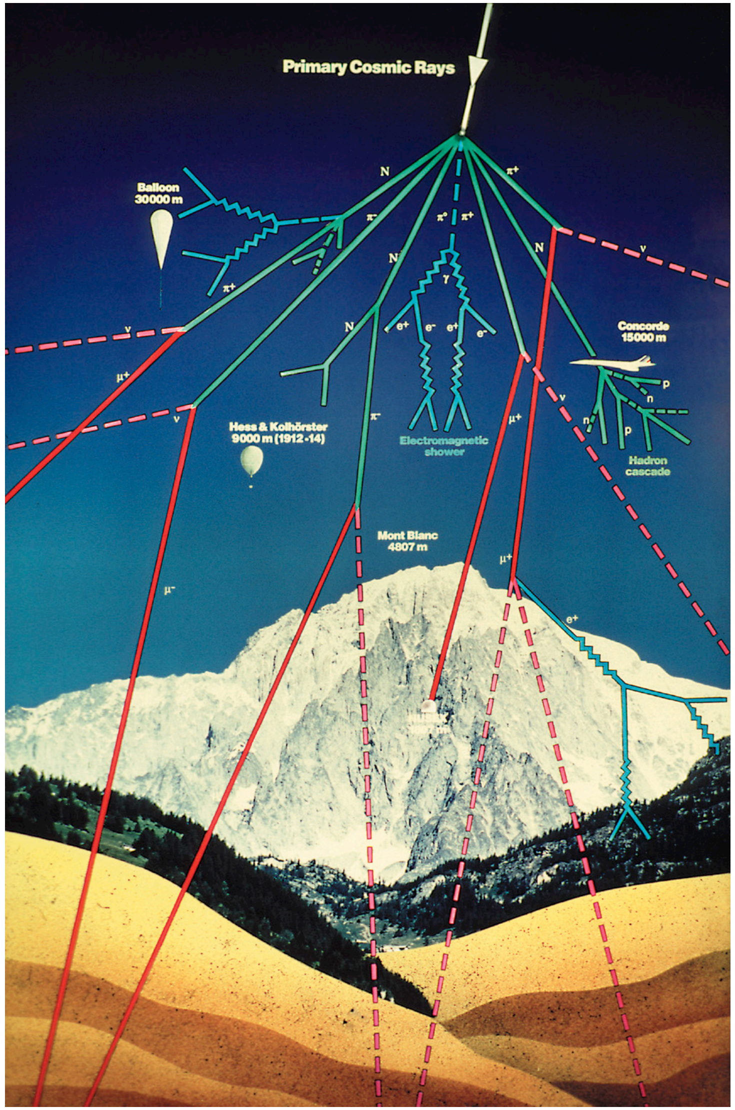
- Energy for life can also come from chemical redox couples generated by geothermal processes
- Geothermal flux can arise from (i) the planet cooling off from its gravitational heat of formation, (ii) decay of long-lived radioactive elements, or (iii) tidal heating for a close-orbiting world or moon
- On Earth only a tiny fraction of the geothermal heat is converted into chemical energy

Planetary atmospheres and habitability

- The existennce of a planetary atmosphere is an essential requirement of habitability
  - A minimum atmospheric pressure at the planet surface is set by the liquid water criterion (or the liquid phase of a solvent alternative to water)
  - The atmosphere also protects the planet surface from ionizing radiation

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



Protective effect of the Earth atmosphere

- Ultraviolet photons
  - The ozone (O_3) 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 that can reach the planet surface

Searching for universal criteria of habitability

The habitability criteria that we have considered are based on the properties of terrestrial life

- Ideally, one would like to find general criteria of habitability suitable for any possible form of life

- A possible strategy consists in searching for a criterion that includes the liquid water criterion as a special case

- As an example, we discuss the “hydrogen bond” criterion

The hydrogen bond criterion of habitability

- Assumption:
  - Any biochemistry based on genetic and metabolic molecules requires a pervasive presence of hydrogen bonds

- We can infer temperature limits of habitability by comparing:
  - the mean thermal energy of the environment, $E_{th}=(3/2)kT$
  - with the characteristic energy of chemical bonds of biological molecules

To prevent the denaturation or disruption of biomolecules it should be:

$$E_{th} < E_{\text{chemical bonds}}$$

Applying this condition to chemical bonds involved in life processes provides temperature limits of habitability

Habitability and energies of chemical 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

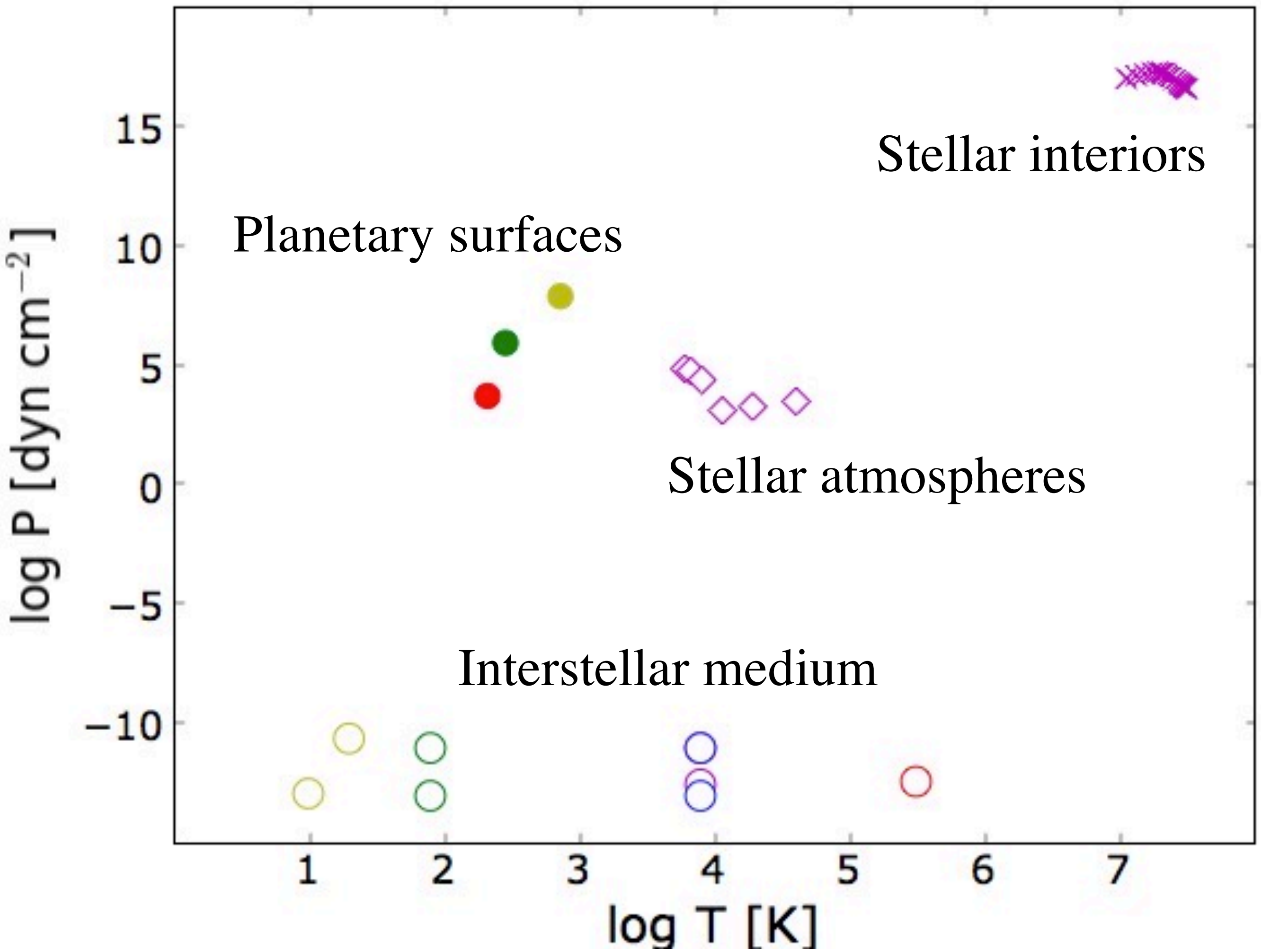
    → 5 kcal/mole ~ 20 kJ/mole ~ 0.2 eV

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

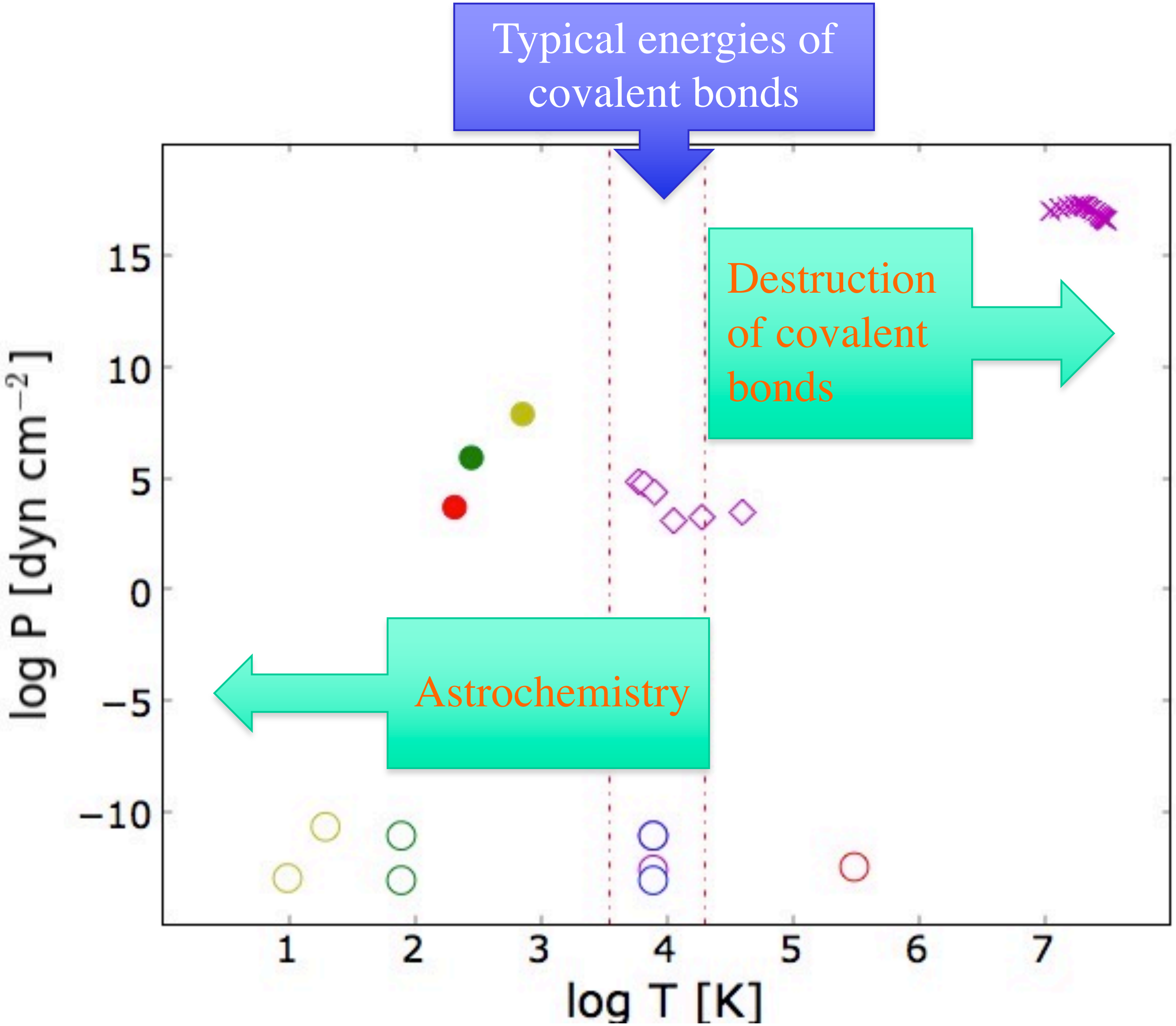
To set limits for the survival of chemical bonds in the diagram T-p we convert the bond energies in temperature units

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

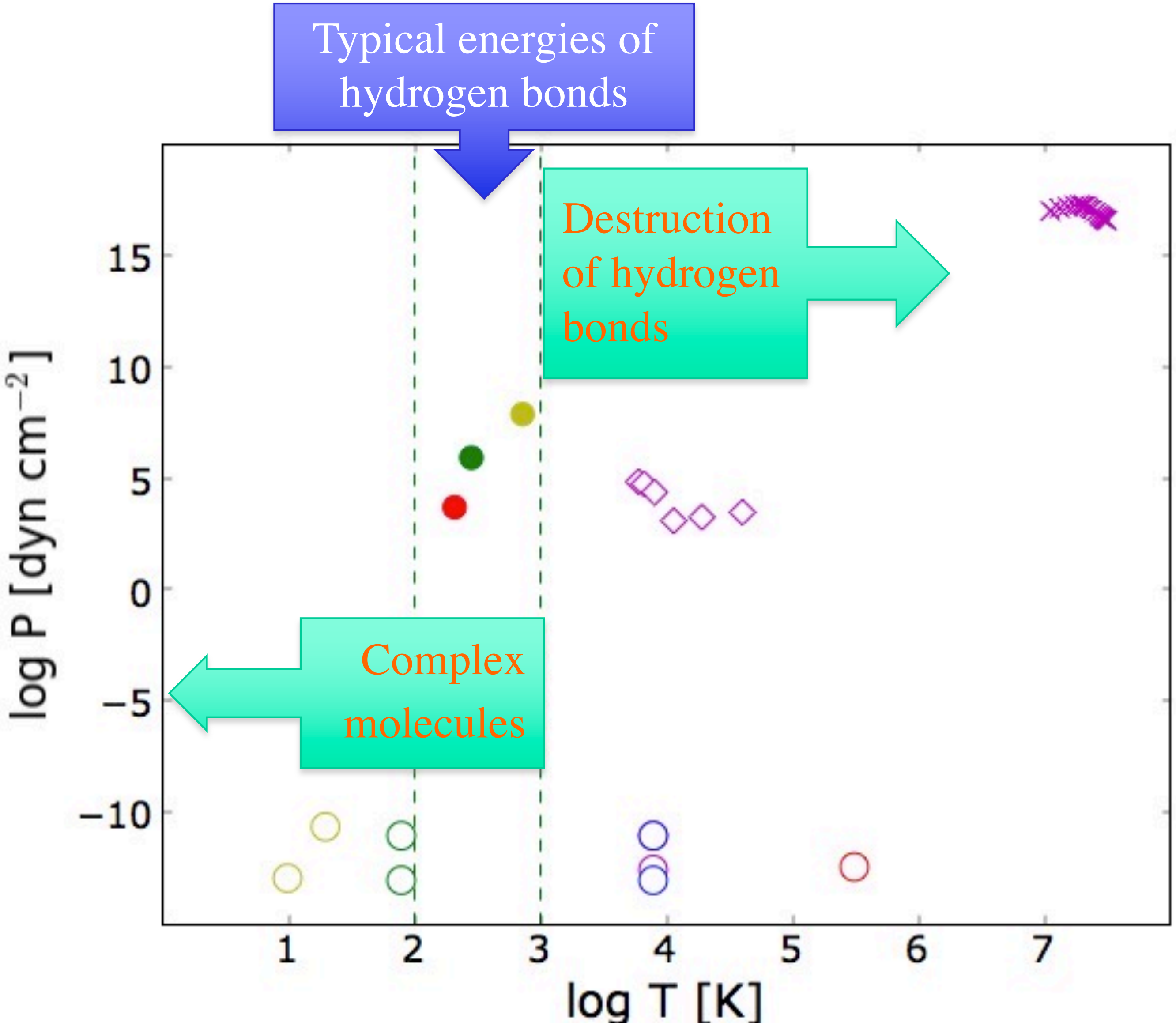
We investigate the survival of different types o chemical bonds



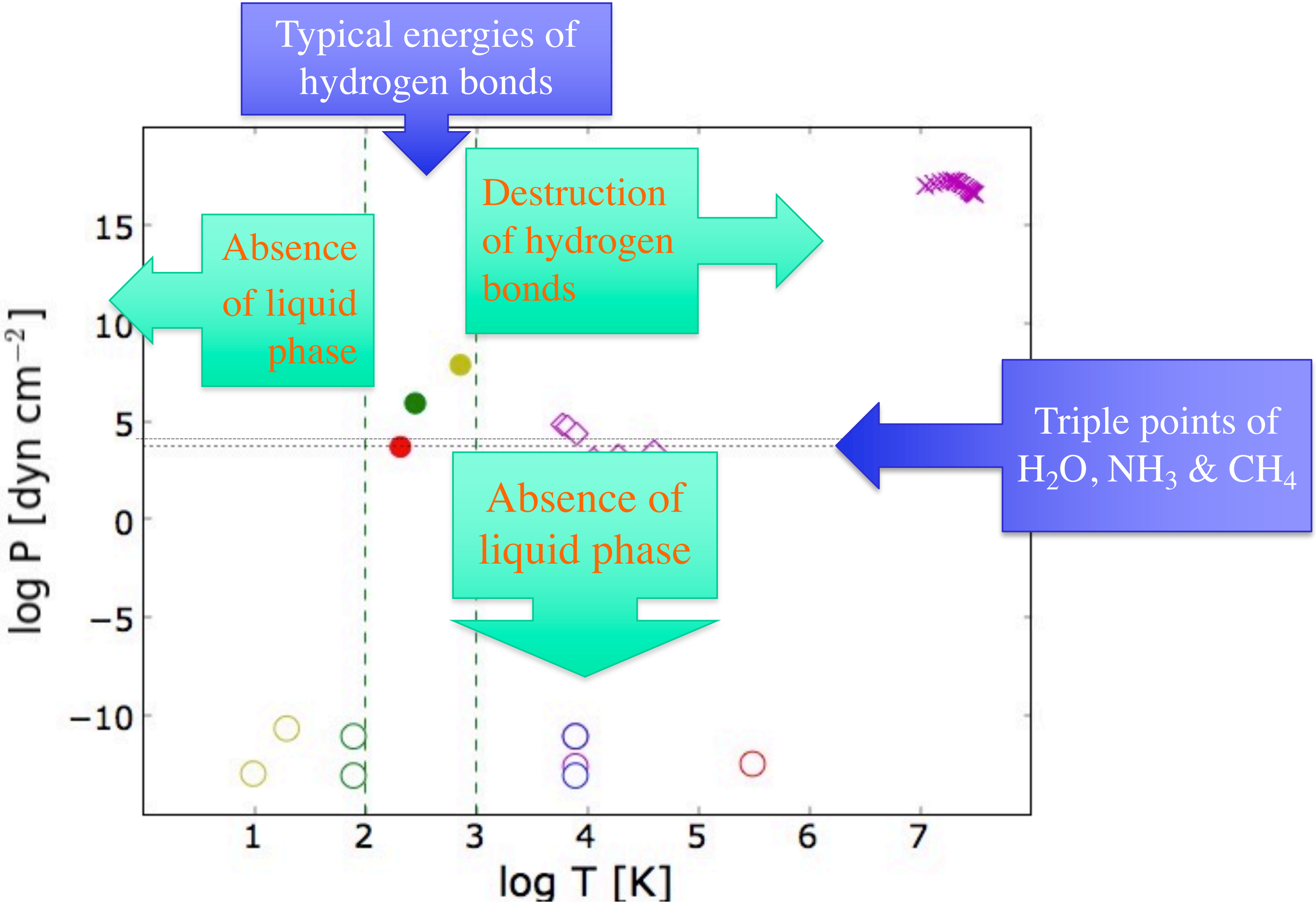
Survival of covalent bonds



Survival of hydrogen bonds



The habitable universe according to the hydrogen bond criterion



The “hydrogen bond criterion” suggests that only planetary systems can provide habitable environments in the universe

- The fact that planets and moons can be located at different distances from their central stars, offers a variety of local climates, some of which may provide habitable conditions
- Since the intermolecular forces between water molecules are hydrogen bonds, the “liquid water criterion” can be considered as a special case of the “hydrogen bond criterion”

Pros & Cons of the “hydrogen bond criterion”

- Is more universal than criteria based on terrestrial life
- It is difficult to set clearcut energy thresholds using the hydrogen bonds, whereas the “liquid water criterion” is well defined from the point of view of the thermodynamical variables (T, p)

Appendix: 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

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:

$$H = \Sigma_R \; w_R \, D_R$$

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

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 $N_{atm}=p/g$ [kg/m^2]

    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