Physico-chemical requirements of planetary 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
- Studies of habitability provide a way of understanding which astronomical environments are potentially suitable for hosting life
- In remote astronomical bodies assessing the potential of habitability is easier than trying to detect life

- 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 <u>natural environments</u> in which life can exist
- Habitability outside Earth
  - In the last decades, the resistence/adaptation of life has started to be tested also in <u>artificial space environments</u> 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 are commonly referred to the surface of the planet or moon
- Surface habitability is of special interest in exoplanets because surface life has the 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 Mars or Europa, life could be present in lakes or oceans below the surface
- In Solar System studies, sub-surface habitability has to be taken into account

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

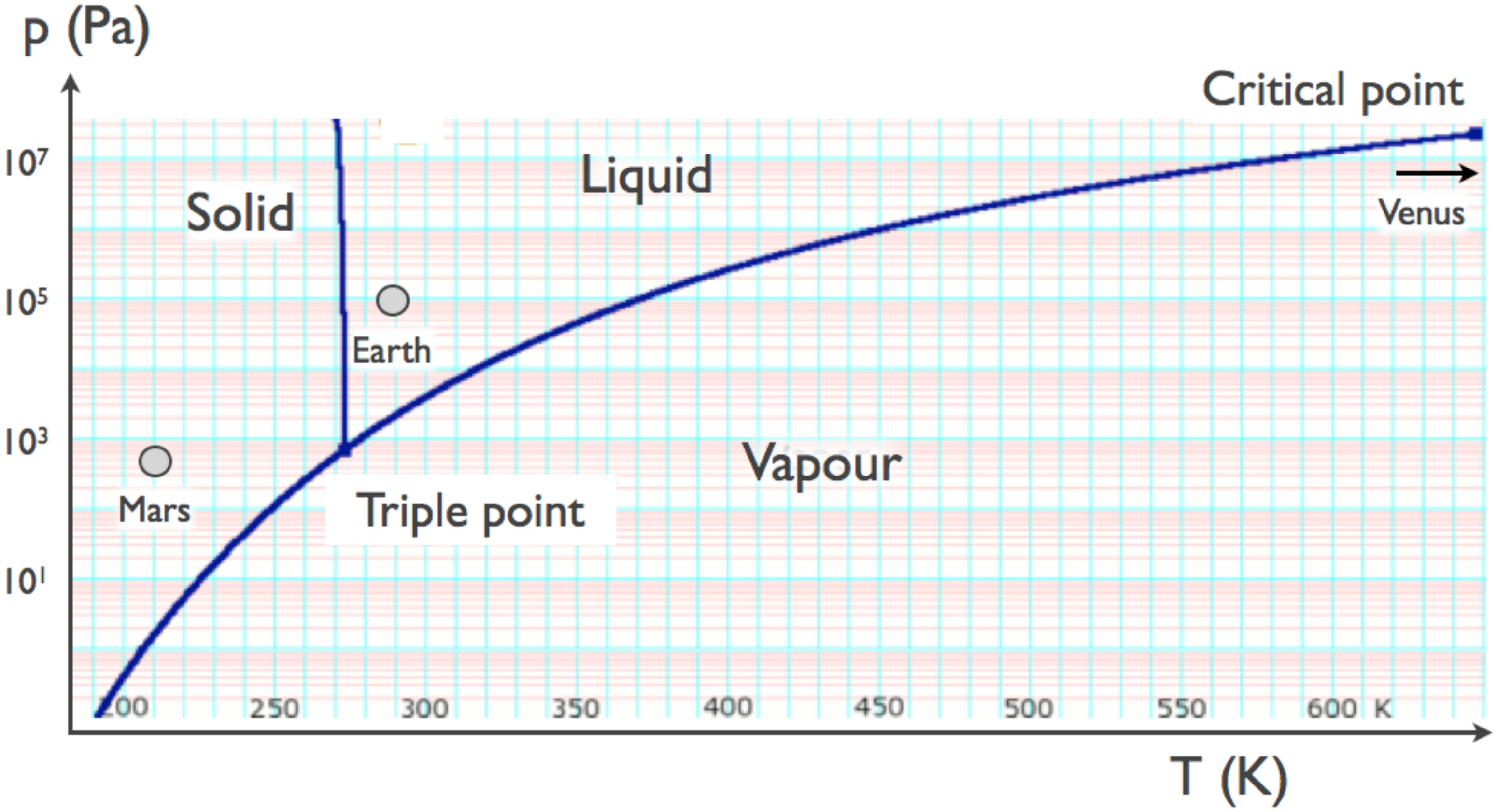
- Water should be present and the thermodynamical conditions of the environment should allow water to be in the liquid phase

The liquid water criterion constrains the ambient temperature and pressure

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

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

$p_s > 611$ Pa



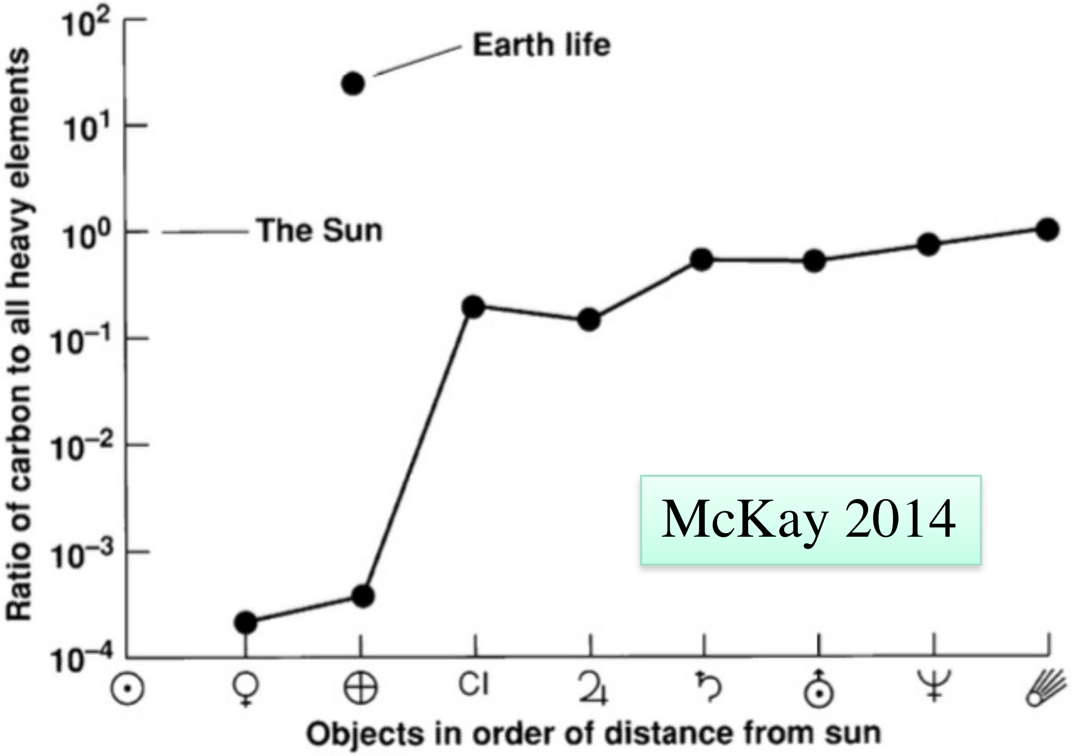
Water abundance and habitability

- Water molecules are built up with cosmically abundant elements
  - 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

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



McKay 2014

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

- Autotrophs 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

- Heterotrophs 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

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:

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

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"

Energy sources for terrestrial autotrophs: oxidation-reduction reactions

- Metabolism based on sulphur

  Example of reaction scheme:

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

  Also this scheme produces energy while fixing organic carbon

  Probably very ancient

  Examples of microrganisms:

  Thiobacillus thiooxidans, Sulfolobus acidocaldarus

  Example of habitat: sulphuric caves

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; the remaining 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

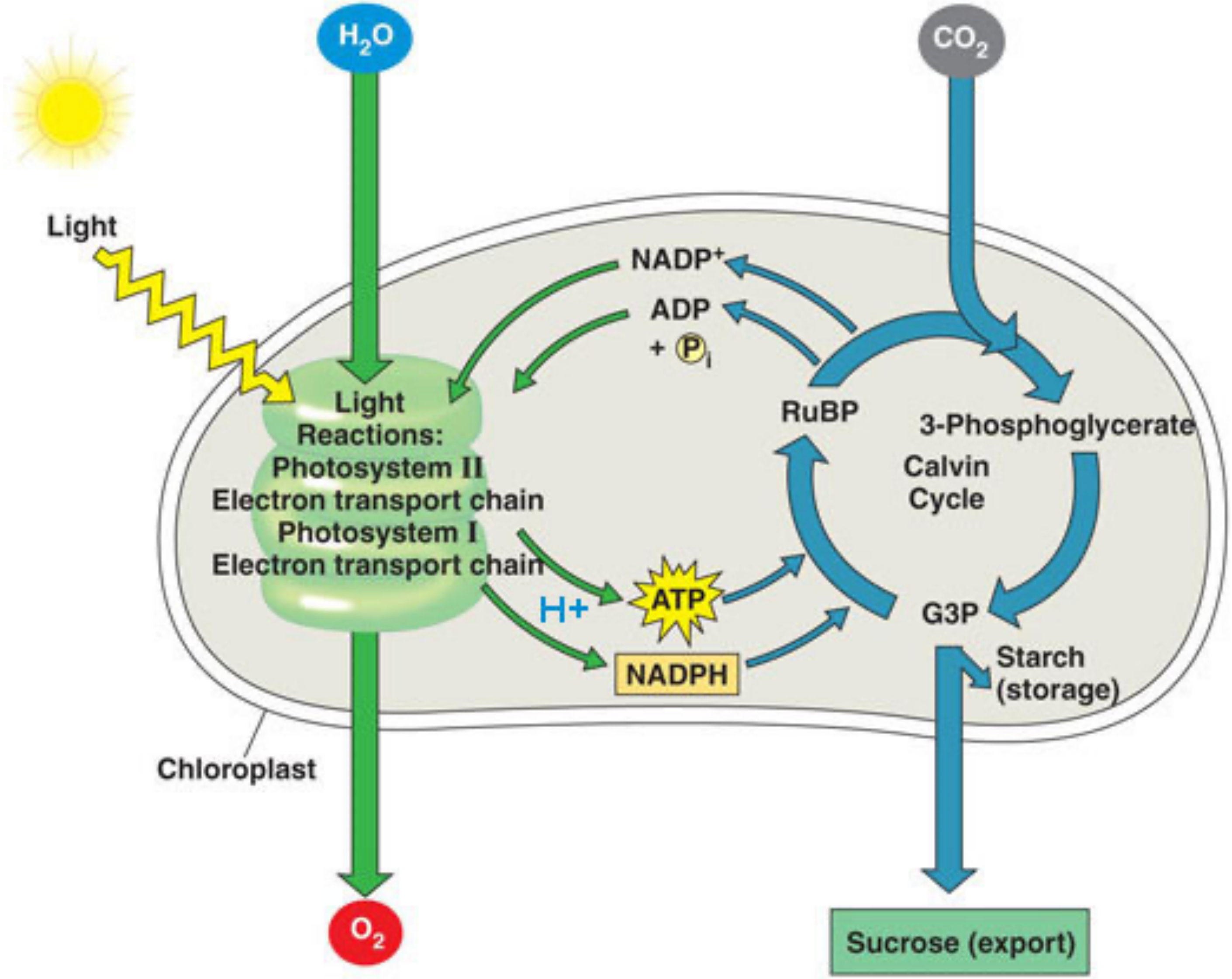
The overall budget of reactants and products in the oxygenic photosynthesis can be expressed in the idealized scheme of reaction

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

- (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

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



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

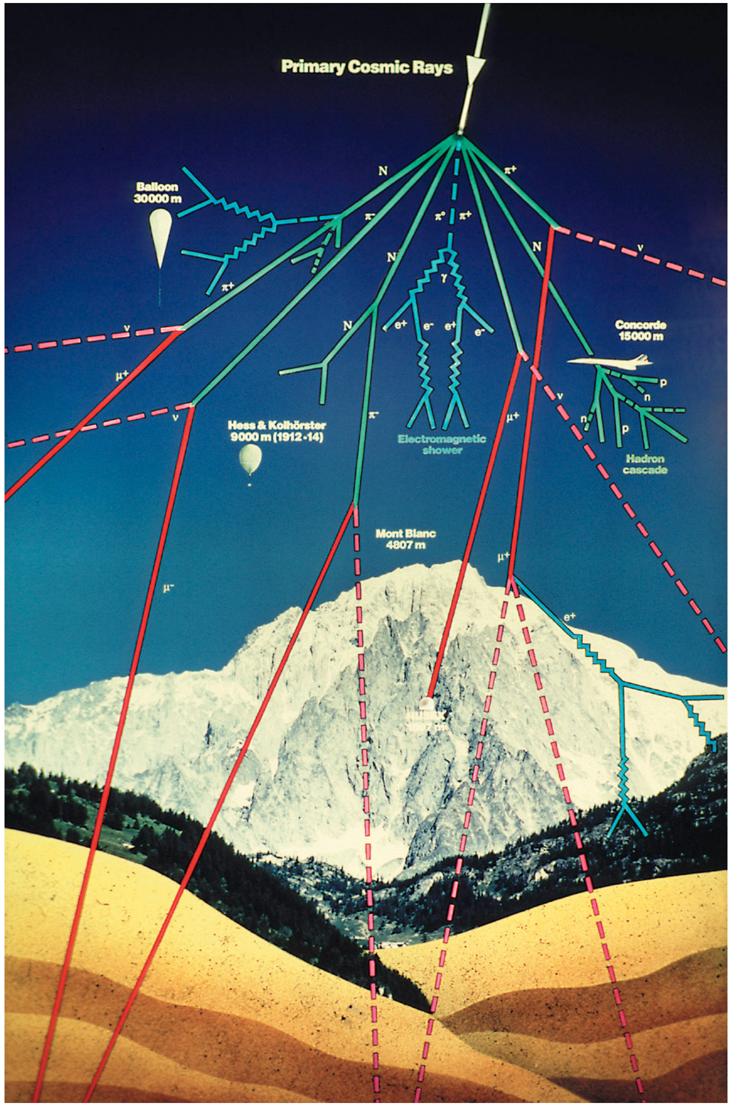
- Energy for life can also come from chemical redox couples generated by geothermal processes
- Geothermal flux can arise from (i) the planet cooling off from its gravitational heat of formation, (ii) decay of long-lived radioactive elements, or (iii) tidal heating for a close-orbiting world or moon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

Planetary atmospheres and habitability

- The presence 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

Radiation dose and life

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

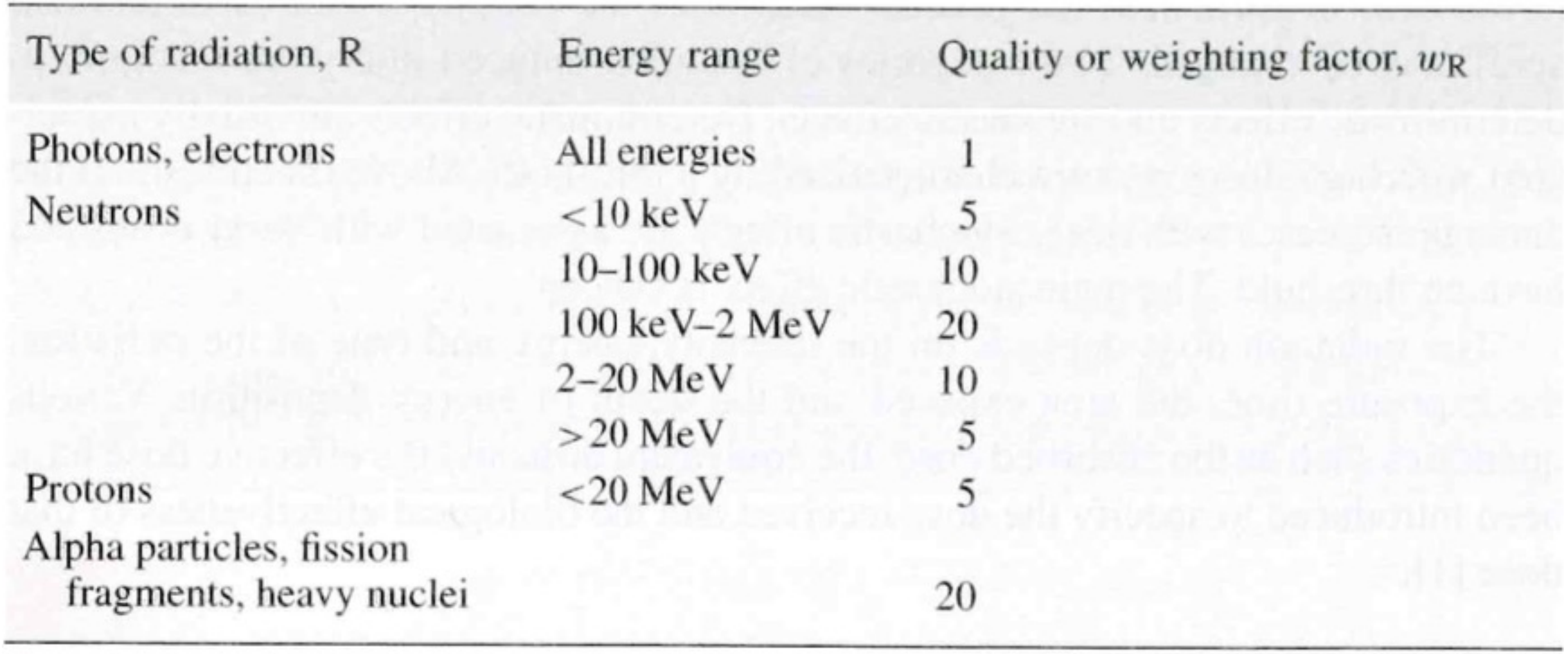
    The SI unit is the gray: 1 Gy = 1 J/kg
  - Biological effects depend not only on the total dose but also on the rate at which this dose is received (e.g. mGy/yr)
- Type of radiation
  - The biological effect also depends on the way in which the energy is deposited along the path of radiation, and this 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

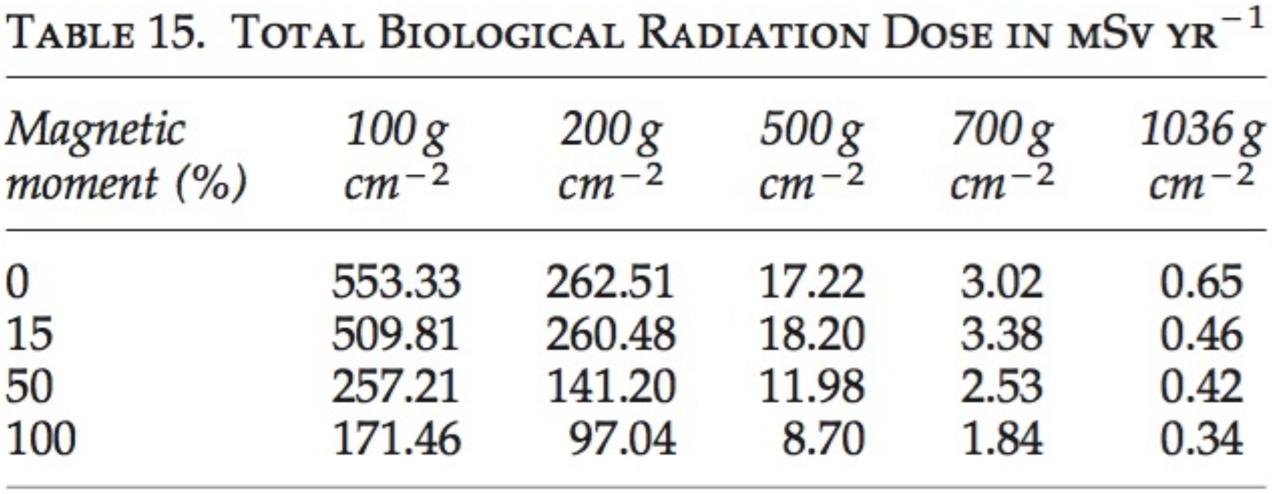


TABLE 15. TOTAL BIOLOGICAL RADIATION DOSE IN mSv yr^{-1}

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

Searching for universal criteria of habitability

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

- Ideally, one should try to adapt the criteria to other possible forms of life
- In particular, it would be important to define a general criterion that would include the liquid water criterion as a special case
- As an example of this possibility, we now discuss the “hydrogen bond” criterion

The hydrogen bond criterion of habitability

- Assumption: any biochemistry based on interactions between genetic and catalytic molecules requires a pervasive presence of hydrogen bonds
- The requirement of hydrogen bonds can provide general criteria of habitability, not specific to terrestrial life

- Example of application:
- Obtaining temperature limits of habitability of a given environment by comparing:
  - –the mean kinetic energy $E_{\mathrm{kin}}=(3/2)kT$
  - –with the characteristic energy of chemical bonds of biological molecules

To prevent the distruction of biological molecules it should be:

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

Applying this condition to weak chemical bonds, such as hydrogen bonds, may provide an upper temperature limit 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

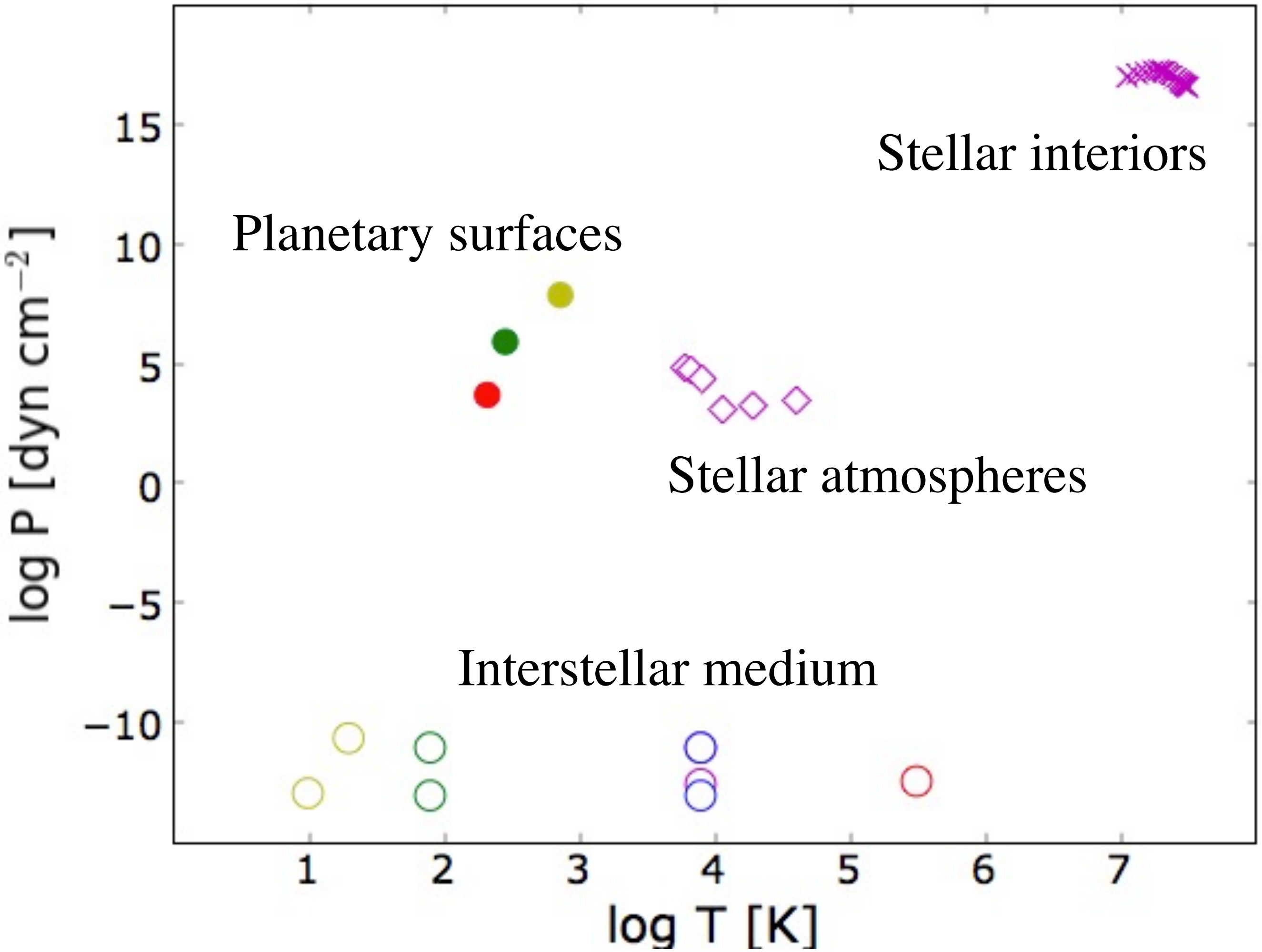
    → 5 kcal/mole ~ 20 kJ/mole ~ 0.2 eV

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

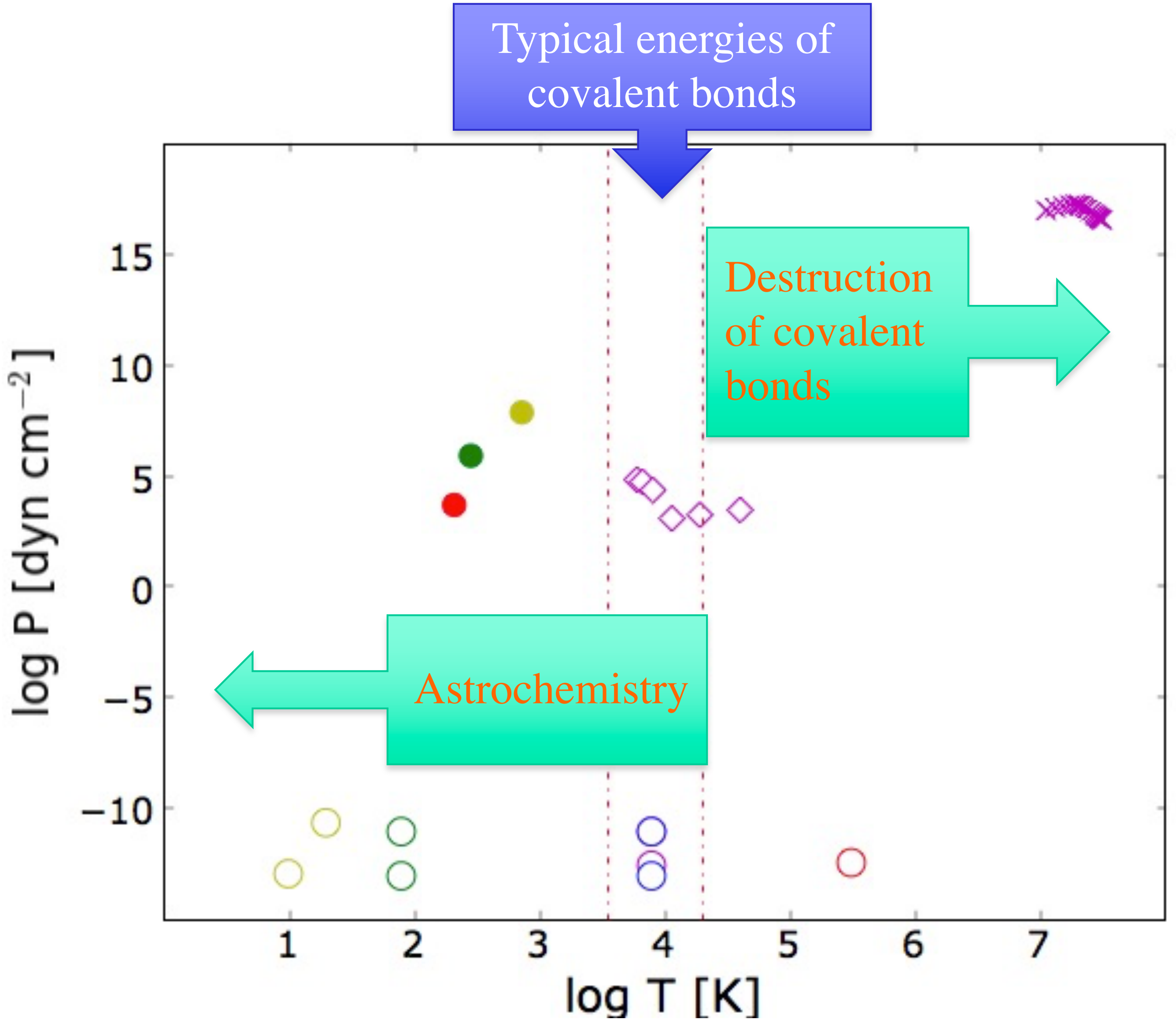
We convert in temperature units the above energies in order to set limits for the survival of chemical bonds in the diagram T-p

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

We investigate the survival of different types o chemical bonds



Survival of covalent bonds

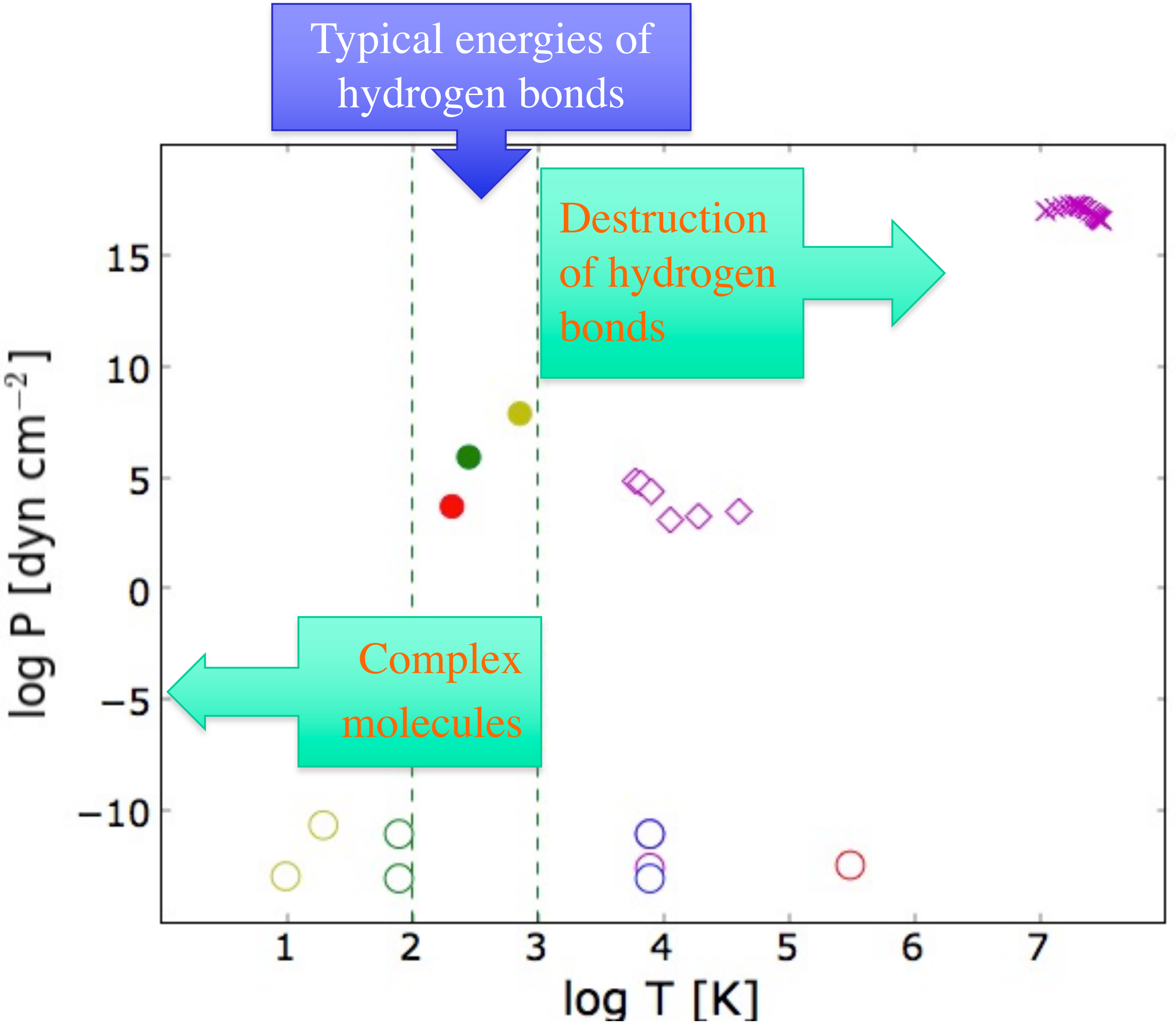


Typical energies of covalent bonds

Destruction of covalent bonds

Astrochemistry

Survival of hydrogen bonds

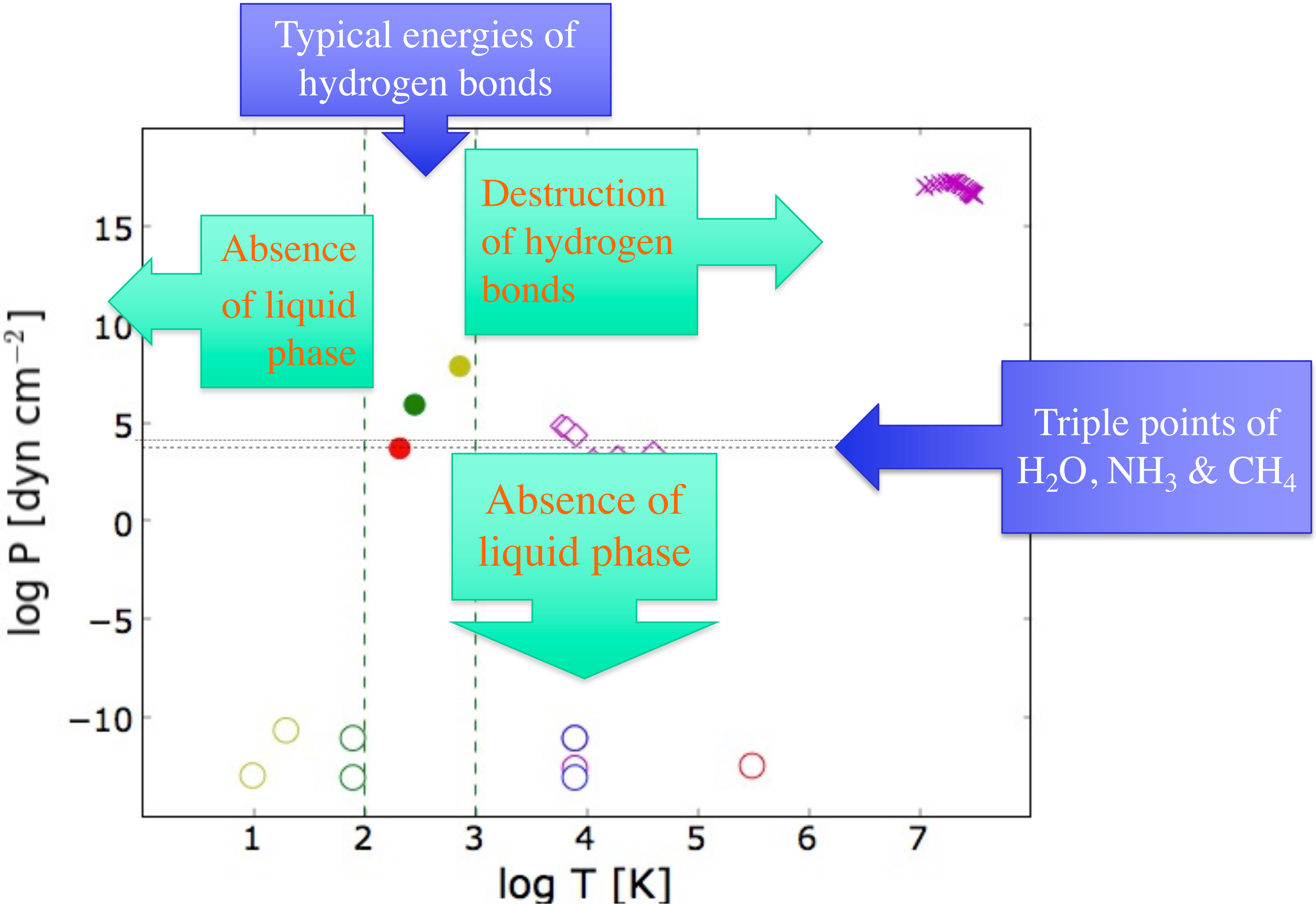


Typical energies of hydrogen bonds

Destruction of hydrogen bonds

Complex molecules

The habitable universe according to the hydrogen bond criterion



Typical energies of hydrogen bonds

Absence of liquid phase

Destruction of hydrogen bonds

Triple points of H_2O, NH_3 & CH_4

Absence of liquid phase

Conclusion:

based on the “hydrogen bond criterion”, only planetary systems can provide 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
- Advantage: the criterion is more universal than criteria simply based on terrestrial life
- Disadvantage: 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)

- The “liquid water criterion” can be considered as a special case of the “hydrogen bond criterion”, because the intermolecular forces of water are hydrogen bonds