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Exploring the habitability of exoplanets with climate models

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Abstract. The search for atmospheric biosignatures in exoplanets is one of the most challenging tasks of observational astronomy. The selection of targets for this search requires a quantitative assessment of the habitability of exoplanets and the detectability of their atmospheres. In this contribution, I show how the surface habitability and atmospheric properties of rocky exoplanets can be explored with the aid of climate models. With proper operational definitions, the habitability can be quantified from a model of the surface distribution of the physical quantities that affect life processes, such as the temperature or the ionizing radiation. The exoplanetary habitability is influenced by many factors not considered in classic studies of the habitable zone (HZ), such as variations of atmospheric pressure and composition, surface gravity, rotation period, axis tilt, and surface geography. Many of these factors are unconstrained by observations, but can be parametrized in climate models in order to assess their impact on the habitability. Considering the need to simulate a broad range of planetary conditions not present on Earth, it is convenient to use climate models of low or intermediate complexity. These models should be preliminarly validated with more complex models featuring the most relevant components and feedbacks of the climate system. In the final part of the contribution, I scrutinize the commonly adopted criteria of habitability, which are based on the properties of terrestrial life. Assuming that life is a universal process sustained by molecular interactions, it is possible to rank the viability of alternative biochemistries according to the hydrogen-bond capabilities of the molecular constituents. This approach suggests that the liquid-water criterion may be appropriate for any form of life that is sustained by genetic and catalytic molecules.

Key words. Extrasolar planets — Climate models — Life in the Universe

1. Introduction

One of the main drivers of exoplanet studies is the quest for inhabited worlds, the best candidates for this search being rocky planets with earth-like levels of insolation. Statistical surveys indicate that the occurrence rate of rocky exoplanets is relatively high (Foreman-Mackey et al. 2014; Fulton et al. 2017) and many earths and super-earths are expected to be detected soon by ground- and space-based observational facilities. For instance, the host stars of the transiting planets detected with TESS (Ricker et al. 2015) are sufficiently bright to perform follow-up, high-resolution spectroscopy and measure the radial velocity signal. Follow-up observations with ESPRESSO (González Hernández et al. 2018), should allow rocky planets with earth-like insolation to be detected in radial velocity not only around late-type stars, but also around solar-type stars. Thanks to the transit and radial velocity data collected with these and other state-of-the-art instruments, the structural properties (e.g. radii and masses) of a sample of rocky exoplanets with earth-like levels of insolation will be soon derived. The search for life in these or other exoplanets may lead to ground-breaking astrobiological results. However, at variance with searches for life in the Solar System, where planetary samples can be analysed, the search for life in exoplanets is restricted to the chemical analysis of their atmospheres. The detection of atmospheric biosignatures is extremely challenging (Schwieterman et al. 2018) and will require the use of the most advanced astronomical facilities with spectroscopic capabilities (Udry et al. 2014; Fujii et al. 2018). Because of this, it is fundamental selecting optimal targets to search for atmospheric biosignatures. Since habitability is a pre-requisite for the generation of biosignatures, an effort is required to refine the tools used to estimate the habitability. So far, assessments of exoplanetary habitability have largely relied on published calculations of the classic habitable zone (Kasting et al. 1993; Kopparapu et al. 2013). The classic HZ considers variations of stellar insolation and spectral type. While there is no doubt that the insolation is a key contributor to the planetary energy budget, it is important to generalize the classic HZ calculations to quantify the impact of all planetary factors that influence the climate system. Moreover, it is important to provide quantitative estimates of habitability that can be related to the potential generation of atmospheric biosignatures.

In the first part of this presentation, I describe a methodology that can be used to quantify the exoplanetary habitability. In the second part, I explain how climate models with different levels of complexity can be applied for calculations of the exoplanetary habitability. In the third part, I discuss to which extent the commonly adopted criteria of habitability can be considered universal, considering the potential existence of biochemistries different from the terrestrial one.

2. Operational definitions of habitability

Studies of the distribution of terrestrial life indicate that life can only exist within specific intervals of physico-chemical conditions of its environment. The limits of such intervals can be used to introduce operational definitions of habitability. Let us call Q a physical or chemical quantity such that life can only exist when $Q_1 \leq Q \leq Q_2$ in the environment. In particular, it is convenient to restrict the attention on the surface environment, because surface life has the best chance to generate a spectroscopic signature in the overlying atmosphere. If we are able to model the surface distribution of Q at different longitudes, λ, latitudes, φ, and time, t, we can define a habitability function

$$H(\lambda, \varphi, t) = \begin{cases} 1 & \text{if } Q_1 \leq Q(\lambda, \varphi, t) \leq Q_2 \\ 0 & \text{otherwise} \end{cases} . \tag{1}$$

By integrating $H(\lambda, \varphi, t)$ over the planetary surface and one orbital period, we obtain and index of mean orbital habitability of the surface

$$h = \frac{\int_{-\pi}^{+\pi} d\lambda \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} d\varphi \int_0^P dt \, [H(\lambda, \varphi, t) \cos\varphi]}{4P} . \tag{2}$$

Other quantitative indices of habitability, such as the mean global habitability at a given time, or the mean orbital habitability at a given longitude or latitude, can be obtained by proper integration of $H(\lambda, \varphi, t)$. In principle, this methodology can be used to provide quantitative indices of habitability for each of the physical or chemical quantity Q taken in consideration. To focus the rest of the discussion, we consider the ambient temperature as an example of physical quantity.

Let us call (T_1, T_2) a temperature interval suitable for the long-term existence of life. To keep low the dimensions of the climate model, we can consider the mean (longitudinally averaged) temperature in a given latitude zone, $T = T(\varphi, t)$. In this case, the habitability function becomes (Spiegel et al. 2008)

$$H(\varphi, t) = \begin{cases} 1 & \text{if } T_1 \leq T(\varphi, t) \leq T_2 \\ 0 & \text{otherwise} \end{cases} , \tag{3}$$

and

$$h = \frac{\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} d\varphi \int_0^P dt \; [H(\varphi, t) \cos\varphi]}{2P} \tag{4}$$

provides a quantitative estimate of the mean surface habitability. The choice of the limits T_1 and T_2 is critical for the practical implementation of this operational definition. In the rest of this Section we discuss different possible choices, showing why the temperature is particularly useful to constrain the habitability.

2.1. The liquid water temperature range

Given the importance of liquid water for terrestrial life, the liquid water temperature interval provides a natural choice for the limits T_1 and T_2 of Eq. (3). In general the surface pressure, p, will differ from the terrestrial one and the pressure dependence of the melting point, $T_1 = T_1(p)$, and boiling point, $T_2 = T_2(p)$, must be taken into account. In this way, Eq. (4) provides a pressure-dependent, liquid-water habitability index, $h_{\mathrm{lw}} = h_{\mathrm{lw}}(p)$. By calculating $h_{\mathrm{lw}}(p)$ as a function of insolation, S, while keeping constant all the other planetary conditions, one can obtain a HZ in the plane (S, p). At variance with the classic HZ, the habitability $h_{\mathrm{lw}} = h_{\mathrm{lw}}(S, p)$ is quantified at each location of the plane (Vladilo et al. 2013). The adoption of a planetary quantity that has multiple impacts on the climate system, such as p, makes this type of HZ particularly instructive. As p increases, the water boiling point increases and, at the same time, the greenhouse effect rises. As a result, the HZ in the plane (S, p) broadens with increasing p. When the pressure is low, the liquid water interval narrows and, at the same time, the efficiency of the heat latitudinal transport decreases, leading to large excursions of surface temperature. As a result, temperature extremes outside the liquid water range become frequent, leading to a decrease of $h_{\mathrm{lw}}(p)$ at low p. More examples of calculations performed with the index h_{lw} can be found in Vladilo et al. (2015) and Silva et al. (2017a).

2.2. Climatological and biological limits

Also climatological and biological considerations provide temperature limits of habitability. At variance with the limits of liquid water, climatological and biological limits are hard to quantify. However, they should not be ignored since life (or at least terrestrial life) cannot be maintained in the long term in the extreme conditions that we now discuss.

In a climatological perspective, the long-term persistence of water on the planetary surface is limited by the onset of the Moist Greenhouse (MG) or the Runaway Greenhouse (RG) effects (Kasting et al. 1993). A terrestrial planet enters in a MG state if the mass mixing ratio of water vapour in the stratosphere becomes sufficiently large to allow for strong UV photodissociation and subsequent loss of hydrogen to space. The planet enters a RG state if the lower atmosphere becomes opaque to IR radiation and a strong positive feedback between temperature and water vapour is established, leading to the complete evaporation of the surface water in geologically short time scales. Climate calculations of the MG and RG effects are uncertain due to the difficulty of modeling the climate system in conditions of high temperature and high water vapour content (Kasting et al. 1993; Leconte et al. 2013; Wolf & Toon 2014; Gómez-Leal et al. 2018). Even if a temperature threshold for the onset of these effects is not well defined, present-day calculations suggest that they may develop above $T \geq 50 \approx 60$ °C. At the extreme of low temperatures, the feedback between temperature, ice cover and albedo may induce a transition of the planet to a snow-ball state if the surface temperature drops below $T \sim 0$ °C at all latitudes. By definition, in the snow-ball state, the ice cover extends from the poles to the equator. The type of life that could be present in these conditions depends on the biological thermal limits that we now discuss.

The strong temperature dependence of life processes (Precht et al. 1973) provides thermal limits based on biological considerations. In the case of exoplanets, we are interested in life that is able to generate atmospheric signatures detectable with remote observations.

This means that we should restrict our attention on: (1) life with active metabolism, because dormient life, with (nearly) suspended metabolism would hardly impact its own environment; and (2) life persisting in the long term, since transient episodes of life would be rarely detectable, as any transient astronomical phenomenon; the long-term persistence implies that life should be able to carry out its cycle of reproduction. In summary, we are interested in *surface life with active cycles of metabolism and reproduction.* Life with these properties can exist within temperature intervals that are narrower than those of dormient life (Clarke 2014).

The organisms whose internal temperature depends directly on the ambient temperature, such as poikilotherms[1](Precht et al. 1973), are particularly well suited to provide temperature limits. It is not convenient to infer such limits from the organisms that can control their internal temperature over a broad range of ambient temperatures, such as homeotherms (Ruben 1995). Since homeotherms emerged from Darwinian evolution of multicellular poikilotherms, the thermal limits of multicellular poikilotherms are relevant for all complex, multicellular life. The approximate thermal interval for active metabolism and reproduction of multicellular poikilotherms is $0 \leq T(°\mathrm{C}) \leq 50$ (Silva et al. 2017a). This interval is also relevant for the biological production of atmospheric O_2 since the metabolism of the main O_2 producers (cyanobacteria and plants) drops outside such interval. It is hard to overemphasize the role of oxygen in this respect, since the oxygenic metabolism is much more efficient that anaereobic metabolism and the presence of significative amounts of atmospheric O_2 is probably a necessary condition for the emergence of complex, multicellular life in any planet (Catling et al. 2005).

Based on the climatological and biological arguments discussed above, it is convenient to define an operational index of habitability h_{050} (Silva et al. 2017a), calculated from Eqs. (3) and (4) by adopting $(T_1, T_2) = (0°\mathrm{C}, 50°\mathrm{C})$. Below the lower limit, the planet would undergo a transition to a snow-ball state, whereas above the higher limit the planet may undergo a MG or RG mechanism. Outside the adopted limits, multicellular life would hardly emerge and, at the same time, the biological production of O_2, a fundamental atmospheric biomarker, would be hampered.

2.3. Habitable Zones based on quantitative indices of habitability

The index h_{050} can be used to calculate a HZ as a function of insolation, S, and of any planetary quantity known to impact the climate system. In this context, a particularly relevant planetary quantity is the atmospheric columnar mass, i.e. the atmospheric mass per unit area at the planetary surface. In hydrostatic equilibrium this quantity is nothing else than p/g, where g is the surface gravitational acceleration. Examples of HZs obtained by calculating $h_{050} = h_{050}(S, p/g)$ while keeping constant other planetary properties (Silva et al. 2017a) are shown in Figs. 1, 2, and 3. The red curves in the figures indicate the approximate location of the insolation that gives rise to the RG instability. The calculations of the index h_{050} are virtually unaffected by the uncertainties inherent to the calculations of the RG instability.

The interest of building a HZ as a function of p/g is two-fold. First, like the surface pressure, p/g influences the greenhouse effect and the efficiency of the horizontal transport. Second, the protection of the planetary surface from ionizing radiation coming from space scales with p/g. At the Earth surface the atmospheric columnar mass is $p/g \simeq 1036$ g cm^{-2}. With the aid of the screening effect of the Earth's magnetic field, this yields a surface dose of radiation of cosmic origin of $\simeq$ 0.3 mSv/year; however, planets with smaller p/g and/or magnetic dipole would experience significant doses of surface radiation (Atri et al. 2013). The shadowed regions in Figs. 1, 2, and 3 indicate the range of values of atmospheric columnar mass for which the surface dose of secondary radiation is higher than 100 mSv/year.

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[1] Poikilotherms include terrestrial plants, invertebrates and ectothermic vertebrates.

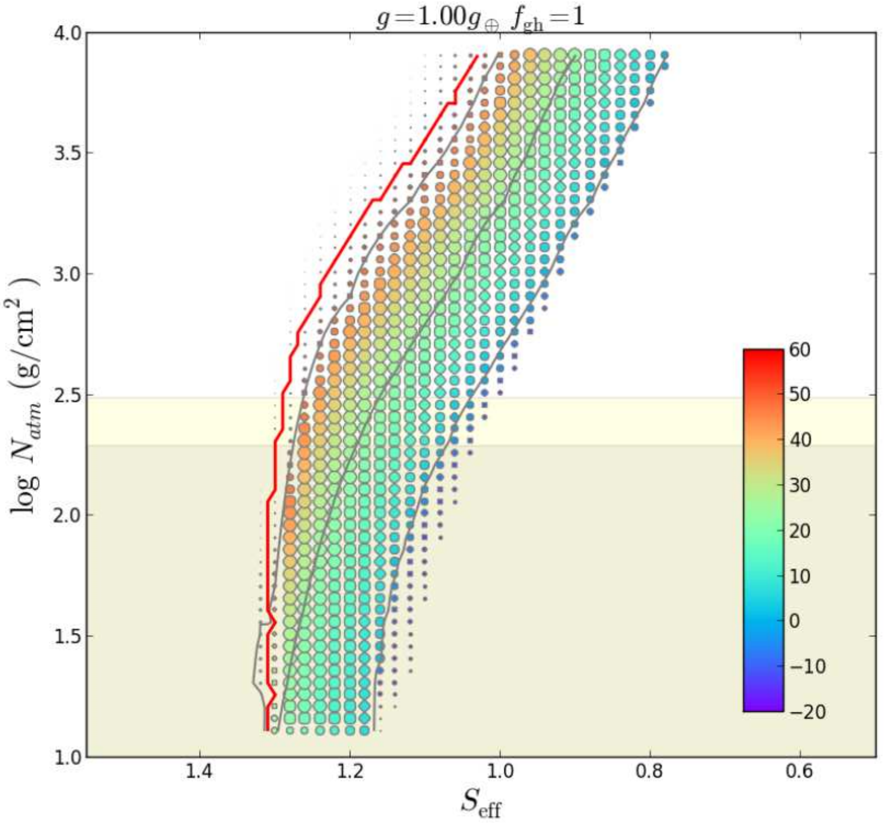

Fig. 1. Habitable Zone of an Earth-like planet with varying insolation, $S_{\rm eff} = S/S_\circ$ ($S_\circ$ = 1360 W m^{-2}) and atmospheric columnar mass, $N_{atm} = p/g$ (the Earth value is N_{atm} = 1036 g cm^{-2}). Each circle represents the result of a climate simulation performed with the ESTM (Vladilo et al. 2015). The size of the circles scales with the habitability index h_{050} (see Section 2.2). The circles are color-coded according to the mean surface temperature of the planet, T_m. An Earth-like atmospheric composition is adopted, with $p\mathrm{CO_2}$ = 380 ppmv. Black curves: isothermal contours T_m = 0, 25 and 50°C. Red line: approximate location of the RG limit. Shadowed regions: range of N_{atm} values where the surface radiation dose of secondary particles of GCRs is >100 mSv yr^{-1} for a planet without magnetic field (yellow) and with an Earth-like magnetic moment (orange). See Silva et al. (2017a) for more details.

3. Climate models and habitability

With the aid of climate models, we can predict the surface distribution of the temperature, or other physical quantities Q, that are required to calculate the habitability according the operational definitions presented in Section 2. A difficulty of this approach is the limited amount of observational data for exoplanets.

In principle, climate models of exoplanets can be constrained with atmospheric spectroscopy, a technique succesfully applied to giant exoplanets with extended atmospheres. However, the routine application of the same technique to rocky exoplanets with thin atmospheres will require the deployment of instruments of next generation. Meantime, we can constrain the models of rocky exoplanets using the data obtained from the transit and ra-

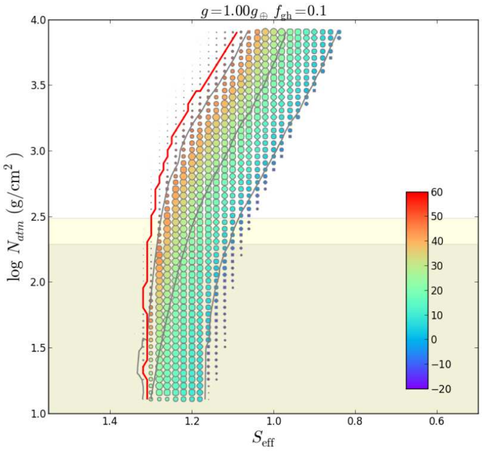

Fig. 2. Same as in Fig. 1, but with lower greenhouse effect (pCO$_2$ = 38 ppmv). As a result, the HZ is shifted to higher values of insolation.

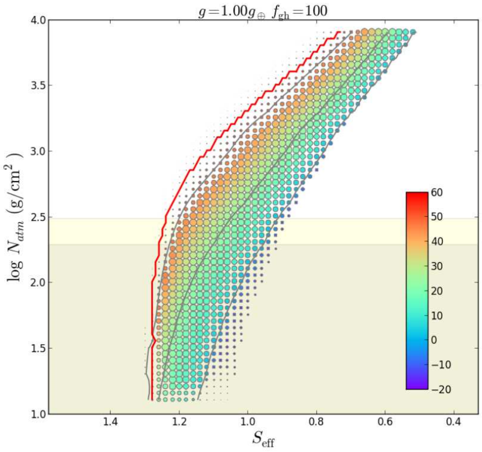

Fig. 3. Same as in Fig. 1, but with higher greenhouse effect (pCO$_2$ = 38000 ppmv). As a result, the HZ is shifted to lower values of insolation.

dial velocity surveys. These data include: planetary structural parameters (radius, mass), orbital parameters (semi-major axis, eccentricity), and properties of the host star (luminosity, spectral type, chemical composition, and age). From the radius and mass we infer the mean density and the surface gravitational acceleration, g. The mean density constrains the internal structure of the planet; g is essential to model the atmospheric stratification. From the orbital parameters and stellar luminosity we infer the insolation, S. All together, the amount of data that can constrain the models is limited. Any additional planetary quantity that impacts the climate system needs to be included as a free parameter in the models. Examples of such parameters are the rotation period, axis tilt, geography, surface pressure, atmospheric composition, and others.

Given the large variety of situations presumably present in exoplanets, models of exoclimates must be adapted to cover a range of conditions not present on Earth and not considered in models of the Earth climate. For instance, exoclimates must be able to provide a physical description of extreme conditions of pressure, temperature, atmospheric composition, water vapour, among others. This is not an easy task. For instance, climate calculations at high temperature and water vapour are rather difficult and uncertain (Leconte et al. 2013). At high surface pressure one should properly consider the pressure dependence of the Collision Induced Absorption and of the Rayleigh scattering in the atmospheric radiative transfer (Keles et al. 2018).

The above mentioned difficulties add to the intrinsic complexity of the climate system (Provenzale 2014). The complexity is due to the presence of several components (e.g. the lithosphere, hydrosphere, cryosphere, atmosphere, etc.) which interact through multiple feedbacks. The feedback between temperature and atmospheric water vapour, and that between ice cover and albedo are essential to assess the habitability, but also other feedbacks are important (e.g. between temperature, clouds and albedo, or between vegetation and precipitation).

An additional complication is that the timescales of the climate system can vary from hours or days, for some processes taking place in the atmosphere, up to years or decades, for some responses of the oceans. As a result, climate simulations including the longest timescales, such as those with oceanic transport, require longer times of execution to attain equilibrium conditions.

Climate models can be more or less complex, depending on which components and feedbacks are included. At the top of the hierarchy of complexity, Global Circulation Models (GCMs) are the more realistic, featuring 3D descriptions of the climate components (including oceans) and incorporating multiple feedbacks. Simulations performed with GCMs are very demanding in terms of CPU time and require a detailed knowledge of planetary conditions, such as the orography, which are not known in exoplanets. Faster climate models with lower complexity are more appropriate for exploring the broad range of conditions that may exist in habitable exoplanets.

Starting from the lowest level of complexity, single atmospheric column calculations, such as those used in the studies of the classic HZ (Kasting et al. 1993; Kopparapu et al. 2013), feature a simplified, radiative-convective treatment of the vertical transport. Longitudinal and latitudinal variations of physical quantities along the planetary surface are not considered. Single column calculations usually adopt an albedo representative of the mean planetary albedo.

Energy Balance Models (EBMs) feature an idealized treatment of the latitudinal energy transport based on heat diffusion (North et al. 1981; Spiegel et al. 2008). With a seasonal and zonal description of the insolation, EBMs yield the simplest estimates of the latitudinal temperature distribution, $T = T(\varphi, t)$. Classic EBMs feature idealized recipes of the OLR (Outgoing Longwave Radiation) and albedo as a function of T. The vertical stratification and longitudinal dependence of physical quantities are not treated in these models.

By incorporating results from single column, radiative-convective calculations in classic EBMs, one obtains 2D (vertical and latitudinal) models with seasonal dependence of the surface temperature (Williams & Kasting 1997; Vladilo et al. 2013). As a refinement of this type of 2D model, the Earth-like planet surface temperature model (ESTM) incorporates a physically-based description of the meridional transport validated with models of higher complexity (Vladilo et al. 2015). The ESTM provides fast estimates of the surface temperature distribution $T = T(\varphi, t)$ and of the habitability h calculated with Eqs. (3) and (4). The HZs shown in Figs. 1, 2, and 3 have been calculated by running a large number of ESTM simulations in such a way to cover parameter space $(S, p/g)$. The same model can also be applied to explore the habitability of invidual exoplanets for a broad range of planetary conditions (Silva et al. 2017b).

Models with longitudinally averaged quantities, such as EBMs and the ESTM, cannot simulate longitudinal gradients of insolation that are not smoothed out by the planetary rotation. These gradients are expected to be present in exoplanets with tidally locked orbital and rotational periods. Planets of this type are frequently found in the classic HZ of late-type stars. To calculate the habitability as a function of longitude and latitude with Eqs. (1) and (2), 3D climate models are required. To keep low the computational cost, one can use 3D models of intermediate complexity (ICMs) with a simplified description of the atmospheric and oceanic transport. Besides providing faster simulations, ICMs have importante advantages compared to GCMs: (1) they may be reconfigured for simulating exoclimates that are far away from the Earth climate; (2) thanks to their lower complexity, the identification of key mechanisms of the climate system is enhanced. An example of ICM used in exoplanetary research is PlaSim (Fraedrich et al. 2005; von Hardenberg et al. 2007). Since 3D models are strongly dependent on the orography, which is unknown for exoplanets, one can use ICMs to simulate ”aquaplanets”, characterized by a shallow layer of water covering the whole planet. By ignoring the oceanic transport, this approach provides relatively fast calculations.

Given the complexity of the climate system and the challenge of simulating non-terrestrial physical conditions, the whole hierarchy of climate models briefly described above should be employed in exoplanetary studies. The models of higher complexity, tested with well-known climates of rocky planets (present Earth, Mars, Venus, paleo-Earth), should be used to validate models of lower complexity. After the validation process, the broad range of exoplanetary conditions that may impact habitability can be explored taking advantage of the flexibility of the models of lower complexity.

4. Steps towards a universal definition of habitability

So far, we have adopted criteria of habitability that are deduced from the properties of terrestrial life. This approach, followed in most studies of astrobiology, is safe in the sense that the habitability criteria derived in this way are linked to life that exists and can be characterized. However, we cannot exclude that life with usual defining properties (e.g. reproduction, metabolism, Darwinian evolution, etc.), but unconventional biochemistries (i.e. chemical or molecular ingredients or processes) may exist outside Earth.

Life with an unconventional biochemistry might thrive in environments that we consider "non-habitable" according to terrestrial criteria, or might generate unexpected biosignatures of difficult identification. Given this unsatisfactory situation, it is desirable to understand to which extent the biochemistry of life, regarded as a universal phenomenon, may deviate from the biochemistry of terrestrial life.

A convenient starting point to constrain whatever form of biochemistry is to focus on the smallest (molecular) structures and their interactions. Indeed, at the level of molecular processes, we may hope to obtain physicochemical constraints from the universal laws of physics and chemistry. This is virtually impossible at the supramolecular or macroscopic level, where the interpretation of the processes is complicated by the existence of countless feedbacks between the multiple components of biological systems.

As a far as the defining properties are concerned, we can regard life as a phenomenon of "reproduction with variations" (Trifonov 2011). At the molecular level, this definition can be translated in "molecular replication with variations". In turn, this requires the existence of molecules able to store and transmit information, i.e. genetic molecules. The (implicit) requirement of an active chemical network — if nothing else, to perform molecular replication — implies the existence of molecules able to reduce energy barriers, i.e. catalytic molecules. Based on the above arguments, from a purely materialistic point of view, we can regard life as a collection of chemical processes sustained by genetic and catalytic molecules. In this generalization of terrestrial life no hypothesis is made on the nature of the genetic molecules (they may differ from the RNA and DNA) or the nature of the catalytic molecules (they may differ from terrestrial proteins).

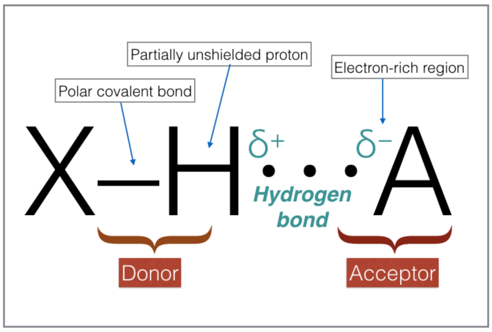

Fig. 4. Sketch of a hydrogen bond between a molecular fragment, X–H, and an atom (or group of atoms), A. The proton in H is partially unshielded because X is more electronegative than H. The atom or group A must possess at least one electron-rich region, such as a lone pair of electrons.

By regarding life as a process sustained by genetic and catalytic molecules, it is possible to constrain the nature of the interactions that take place between such molecular constituents. Of all known chemical bonds and forces, only hydrogen bonds (Fig. 4) are able to mediate the directional interactions of lower energy that are needed for intermolecular recognition and, more in general, for the operation of genetic and catalytic tasks (Vladilo & Hassanali 2018).

Therefore genetic and catalytic molecules must have extensive capabilities of hydrogen bonding. This is also true for the molecular medium in which such molecules are embedded, which must provide active support and mobility. The importance of hydrogen bonds is reinforced by the fact that the quantum effects peculiar of hydrogen bonding are needed

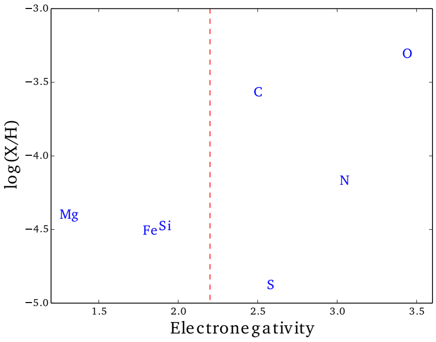

Fig. 5. Electronegativity of cosmically abundant elements. Vertical axis: cosmic abundance by number (Asplund 2009). Vertical dashed line: electronegativity of hydrogen. Only the elements more electronegative than hydrogen, such as C, N, O or S, can form hydrogen bonds; the difference in electronegativity determines the strength of the hydrogen bond.

Table 1. Hydrogen bond properties of cosmically abundant molecules and of molecules of prebiotic interest.

	N_D [a]	N_A [b]	HB network
H_2O	2	2	Yes (3D)
NH_3	3	1	Yes (1D)
CH_4	4	0	No
CH_3NO	3	3	Yes (3D)
HCN	1	1	Yes (1D)

[a] Number of hydrogen donors in each molecule (see Fig. 4); [b] Number of lone pairs of electrons in the outer shells of C, N or O which act as hydrogen-bond acceptors (see Fig. 4).

to build a dynamical system of fluctuating conformations, typical of life.

The hydrogen-bond requirements of life constrains the viability of hypothetical biochemistries alternative to the terrestrial one. This is due to the fact that hydrogen bonds can only be formed with atoms more electronegative than hydrogen (Fig. 5). The capability of forming hydrogen bonds probably explains why O, N and C are present (and Si is absent) in active sites of the genetic and catalytic molecules of terrestrial life.

A molecular medium generating a hydrogen-bond network is essential to actively support the activity of genetic and catalytic molecules. The capability of forming a network of hydrogen bonds indicates which molecules are best suited to form the molecular medium of life. Among cosmically abundant molecules, water, ammonia and methane have decreasing capability of forming a network of hydrogen bonds (Table 1). Among these molecules, only water can form a 3D network. Remarkably, molecules that play succesful roles in prebiotic pathways, such as hydrogen cyanide and formamide (Saladino et al. 2019), have good capabilities of hydrogen bonding (last two lines of Table 1). This suggests that hydrogen-bond interactions may be relevant for the emergence of life processes.

In summary, the biochemistry of life, regarded as a universal phenomenon sustained by genetic and catalytic molecules, is severely constrained by the requirements of hydrogen bonding (Vladilo & Hassanali 2018). In this perspective, biochemistries based on water are more efficient than hypothetical biochemistries based on ammonia. The lack of hydrogen-bond acceptors in the CH_4 molecule casts doubts on the viability of a biochemistry based on liquid methane. As in terrestrial life, N and O atoms are the best suited to form hydrogen bonds in the active sites of genetic and catalytic molecules, while Si atoms are not suited for the same purpose. Taken together, the above indications suggest that the biochemistry of life in the universe may not deviate significantly from that of terrestrial life. If this is the case, the habitability criteria based on the properties of terrestrial life may be representative, to some extent, of any form of life based on genetic and catalytic molecules.

5. Conclusions

The study of exoplanetary habitability is a priority of current astronomical research that poses serious challenges. One concerns the adoption of operational definitions of habitability based on the response of life to variations of physical or chemical conditions of the environment. Another challenge is the development of climate models sufficiently flexible to explore the broad range of conditions that may be present in rocky exoplanets. Finally, a particularly difficult challenge is to find criteria of habitability more universal than those based on the properties of terrestrial life.

From a practical point of view, it is desirable to produce new calculations of the HZ taking into account the impact on habitability of planetary quantities not considered in the classic HZ. The methodology and examples described above show examples of HZs calculated as a function of the atmospheric columnar mass, p/g. By extending this approach to other quantities, one can build a multi-dimensional HZ, each dimension being representative of a planetary quantity that is known to influence the climate system.

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