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Planetary entropy production as a thermodynamic constraint for exoplanet habitability

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ABSTRACT

Any biosphere emerges, lives, and grows producing entropy. Entropy production is a thermodynamic function crucial in the framework of non-equilibrium thermodynamics as it is directly related to the dynamical behaviour of far-from equilibrium systems. The extent of entropy production is proportional to the ability of such systems to dissipate free energy and thus to 'live', to evolve, to grow in complexity. Generally, a certain threshold of entropy production must be exceeded for the emergence of complex self-organizing structures. Thus, the entropy production can be considered as the thermodynamic thrust that drives life emergence and evolution. In this perspective, we propose that the value of the planetary entropy production (PEP) can provide a first order estimate of the thermodynamic potential of planetary environment to sustain a complex biosphere. Here we use a simplified approach to evaluate the upper limit to the PEP and to the corresponding free energy as function of stellar temperature and orbital parameters of the planet. We found that only Earth-like planets in the circumstellar habitable zone (CHZ) of G and F stars can have a PEP value higher than the Earth value. Further significant thermodynamic differences exist between the inner and outer edge of the CHZ, with the inner edge being thermodynamically more advantageous for the development of complex biospheres. Interestingly, among the recently proposed habitable exoplanets, the ones belonging to the Hycean planets appear the thermodynamically best candidates.

Key words: astrobiology – terrestrial planets.

1. INTRODUCTION

In 1886 Boltzmann stated that 'the general struggle for existence of living beings is therefore not a fight for energy, which is plentiful in the form of heat, unfortunately untransferable, in everybody. Rather, it is a struggle for entropy that becomes available through the flow of energy from the hot Sun to the cold Earth' (Boltzmann & Groot 1974). Although this Boltzmann quotation is incontrovertible as it is based on the second law of thermodynamics, the question of the entropy available for the development of a potential biosphere on extraterrestrial planets is not generally taken into consideration. However, to live, we produce entropy, and the same thing holds for any natural, and thus irreversible, process (Anderson & Stein 1987; Ulanowicz & Hannon 1987; Kondepudi & Prigogine 2015). Conversely, the extent of entropy production is a measure of the activity of the system as it is proportional to the ability of such system to dissipate free energy and thus 'to live', to evolve, to build something (e.g. a biosphere) (Kleidon 2009). Indeed, the degree of entropy production in a system is a measure of how much that system is far-from equilibrium, a necessary condition for the emergence of self-organizing complex structures. Such structures are generated and maintained by free-energy dissipating and entropy producing irreversible processes, thus their very existence and maintenance depend on the dissipation rate. Even more, non-equilibrium thermodynamics has shown that a certain threshold of entropy production must be exceeded for the emergence of self-organizing structures (Prigogine & Stengers 1988). Such far-from-equilibrium structures, called 'dissipative structures', can emerge, 'live' and grow exporting the entropy they produce in the surroundings. Generally, the greater is the overall entropy production in the system and more complex are the dissipative structures in both space and time (Prigogine et al. 1972; Lloyd & Pagels 1988; Kondepudi & Prigogine 2015). In this context, life appears as the supreme manifestation of the self-organizing processes occurring in far-from-equilibrium conditions (see e.g. Prigogine et al. 1972; Michaelian 2011). The connection between the entropy production and biosphere evolution has been highlighted by Schrodinger about 80-yr ago and since then taken up by various authors (Morowitz, 1979; Schneider and Kay, 1994; Schrödinger 1944; Ulanowicz & Hannon 1987). Despite these considerations, the classical definition of the circumstellar habitable zone (CHZ) is restricted to the requirement to have liquid water on the planet surface (Kasting et al. 1993; Dole 2007). Commonly, the inner edge of the habitable zone is determined by loss of water via the runaway greenhouse effect and the outer edge by maximum greenhouse effect (Kasting et al. 1993; Kopparapu et al. 2013). Although liquid water is reasonably needed for life, the existence of a planet in the CHZ does not imply that it will be able to support 'thermodynamically' a biosphere: any life forms (and any natural processes that support it) need to produce entropy over

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time without reaching the thermodynamic equilibrium. Inevitably, for any production of entropy to remain sustainable over the time-scale of biological evolution, a corresponding negative entropy flux with the external space is mandatory (Lineweaver and Egan 2008; Kleidon 2009). Indeed, to be sustainable, the planetary entropy production (PEP) rate can be at most equal to the negative entropy flux with the outer space (Schramski et al. 2015). Thus, the PEP rate value under steady-state conditions represents a fundamental thermodynamic limit to the growth in the planet, to what is possible to build and sustain on the planet (including a complex biosphere). As for all the thermodynamic constraints, the biological need of available entropy is universal and thus its extent can be useful, in combination with other requirements (i.e. existence of liquid water), to constrain exoplanets habitability. The aim of this paper is to provide, with a simplified approach, the upper limit to the PEP and to the corresponding free energy as function of stellar temperature and orbital parameters of the planet. We than evaluate the PEP and free energy for a sample of candidate habitable planets (both Earth-like and not) and compared the results with the Earth. In section 3 we summarize our results and further discuss the reasons that makes PEP a potential marker in the evaluation of exoplanet habitability.

2. EVALUATION OF PEP AND FREE ENERGY FOR EARTH-LIKE EXOPLANETS

To quantify the upper limit of a sustainable PEP rate, we assumed steady-state conditions. Under these conditions, the entropy production inside the planet is exactly balanced by the entropy exchange with the outer space. As known, the larger contribution to planetary ingoing and outgoing entropic fluxes with the external space is by far due to the radiative entropic fluxes. The ingoing entropy flux due to the host stellar radiation can be evaluated assuming that the star of radius R_S is a blackbody with an effective temperature T_S. The radiation entropy per unit time and unit area is given by the Planck's law of a blackbody (Planck 1914; Rosen 1954):

$$S = \frac{4}{3}\sigma T_S^3. \tag{1}$$

The radiative entropy flux at the top of the atmosphere of the planet at distance d from the star is:

$$S_1 = \left(\frac{R_S}{d}\right)^2 \frac{4}{3}\sigma T_S^3. \tag{2}$$

This entropy flux is intercepted by the planet over a disc of cross-sectional area πR_p^2 and averaged over the entire surface of the planet thus giving a net entropy received per unit area and unit time of:

$$S_{\rm in} = \frac{1}{4}(1 - A)\, S_1, \tag{3}$$

where A is the planetary albedo which takes into account the fraction of incident radiation which is reflected in space and generally is taken as 0.3 for Earth-like planets. Assuming uniform day–night energy redistribution the equilibrium temperature for the planet is:

$$T_P = \sqrt[4]{\left(\frac{R_S}{2d}\right)^2 (1 - A)\, T_S^4}. \tag{4}$$

In the hypothesis that also the planet can be considered a blackbody, the corresponding outgoing entropy flux is:

$$S_{\rm out} = \frac{4}{3}\sigma T_P^3. \tag{5}$$

Note that, the equilibrium temperature, although different from the actual surface temperature, is all we need to compute the outgoing entropy flux for the given exoplanet. The net entropy flux exchanged by the planet with the outer space will be:

$$\frac{{\rm d}_e S}{{\rm d}t} = S_{\rm in} - S_{\rm out} \tag{6}$$

$$\frac{{\rm d}_e S}{{\rm d}t} = \frac{1}{4}(1 - A)\, S_1 - \frac{4}{3}\sigma T_P^3. \tag{7}$$

In the hypothesis of steady-state conditions the entropy of the system does not change with time, and we can write:

$$\frac{{\rm d}S}{{\rm d}t} = \frac{{\rm d}_i S}{{\rm d}t} + \frac{{\rm d}_e S}{{\rm d}t} = 0 \tag{8}$$

and

$$\frac{{\rm d}_i S}{{\rm d}t} = -\frac{{\rm d}_e S}{{\rm d}t}, \tag{9}$$

where the left term in equation (9) is the entropy production due to all the irreversible processes happening in the system (Kondepudi and Prigogine, 2015). Combining equations (2), (7), and (9), we can write the upper limit for the PEP per unit time and unit area as follow:

$$\frac{{\rm d}_i S}{{\rm d}t} = \frac{\sigma}{3}\left[4T_P^3 - (1 - A)\left(\frac{R_S}{d}\right)^2 T_S^3\right] \tag{10}$$

under steady-state assumption, also the free energy of the planet remains constant and the rate at which the free energy is dissipated is directly proportional to the rate of entropy production as follow (see e.g. Lineweaver & Egan 2008):

$$\frac{{\rm d}_i G}{{\rm d}t} = -T_P \frac{{\rm d}_i S}{{\rm d}t}. \tag{11}$$

In other words, the entropy production is related to the ability of the system to continuously dissipate free energy and thus to evolve, 'to live', to sustain a biosphere. To note that equation (11) represents the free energy delivered on the planet by the stellar photons and set also the maximum of the radiative energy that can be converted in other forms of free energy before dissipation. Of course, the fraction of this free energy converted in other forms of free energy will depend on the specific mechanism involved (Frank et al. 2017).

To compute the entropy production for exoplanets at the inner and outer edges of the CHZ around main sequence stars with a given luminosity L, the distance d in equation (10) was computed by using the formula derived by Kopparapu et al. (2013):

$$d = \left(\frac{L/L_\odot}{S_{\rm eff}}\right)^{0.5}, \tag{12}$$

where $L_\odot$ is the solar luminosity and $S_{\rm eff}$ is a measure of the flux received by the planet. Here we focused on stars with effective temperature between 2600 and 7200 K and a model of Earth-like planet (i.e. with mass and atmospheric composition similar to Earth). In the model the CHZ inner and outer edge correspond to the runaway greenhouse and maximum greenhouse effects, respectively (see Kopparapu et al. 2013). Of note that substitution of equation (12) into equation (10) makes the entropy production not dependent on the stellar radius. Fig. 1 shows the PEP as function of the effective stellar temperature for the inner and outer edges of CHZ, together with the corresponding available free energy per unit area and unit time. Both the entropy production and free energy increase monotonically with the effective stellar temperature and decrease with the distance from the star. PEP increases of about 70 per cent for the OHZ and 40 per cent for the IHZ over the simulated temperature range. Interestingly the relative increase of the corresponding free energy, in the same temperature range, is higher reaching 100 per cent in OHZ and about 55 per cent in IHZ showing that free energy has a

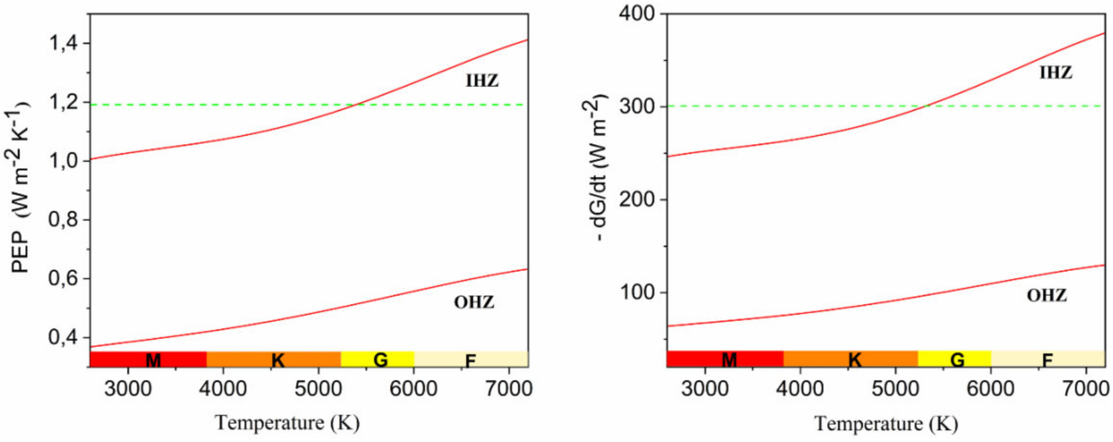

Figure 1. Planetary entropy production (left) and corresponding free energy (right) at the inner edge (IHZ) and at the outer edge (OHZ) of the CHZ of an Earth-like planet as function of the star effective temperature. The horizontal dotted line shows the corresponding Earth values.

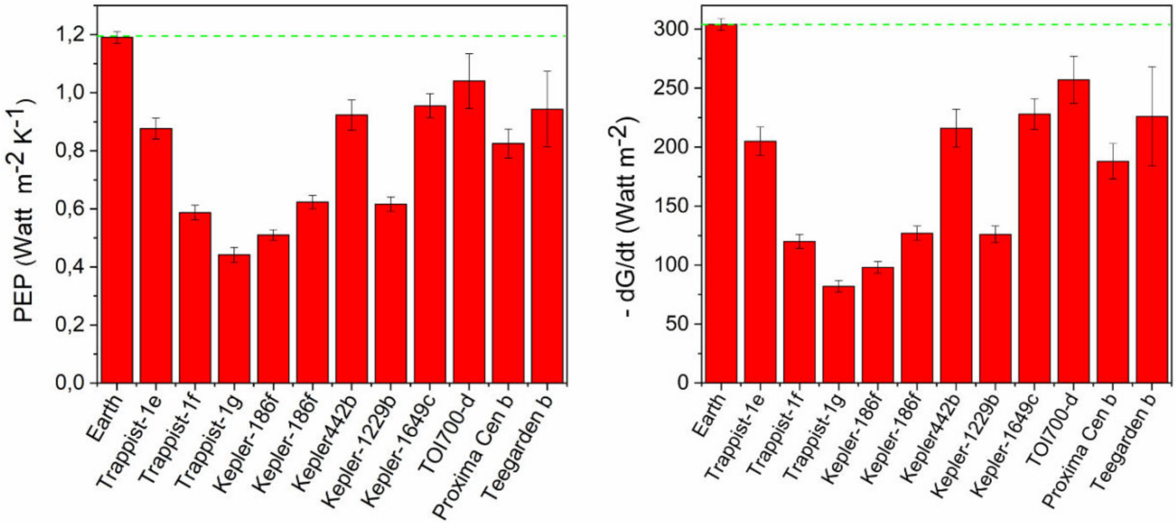

Figure 2. Planetary entropy production (left) and corresponding free energy (right) for known Earth analogues. The horizontal dotted line shows the corresponding Earth value.

stronger dependence on the stellar effective temperature than PEP. As expected, the PEP and free energy values for the Earth correspond to the ones of a planet close to the IHZ of a G-type star. Inspection of Fig. 1 clearly shows that M and K stars cannot sustain Earth-like PEP and corresponding free energy remaining within their CHZ. Even for G and K starts there are large difference of PEP and free energy between the IHZ and OHZ revealing that, at least from a thermodynamic point of view, the inner edge of CHZ is in all cases a much better place to live. Assuming that the value of Earth's PEP is a necessary condition for the development of an Earth-like biosphere, it turns that only exoplanets around G and F stars and close to the inner edge of the CHZ can sustain the terrestrial PEP and, likely, a biosphere as complex as the Earth's. To note that exoplanets in the CHZ of F stars have higher PEP and free energy values than around G stars suggesting that can potentially develop a greater biosphere in comparison with Earth and be more habitable. However, the shorter lifetime of F stars could partially counterbalance the higher PEP value, making the planets in the G stars CHZ the best candidates for the development of a complex biosphere. This result is in line with other studies suggesting that exoplanets around G stars are the best places where to look for habitable exoplanets (see e.g. Lingam & Loeb 2018; Haqq-Misra 2019).

3. EVALUATION OF PEP AND FREE ENERGY FOR CANDIDATE HABITABLE EXOPLANETS

We employed equations (10) and (11) to evaluate the entropy production and the free energy for a sample of proposed habitable planets. We first focused on known Earth analogues within the conservative host star CHZ, assuming that the albedo is the same of that of the Earth. Data from the sample of Earth analogues were extracted from the NASA Exoplanet Archive (https://exoplanetarchive.ipac.caltech.edu/). Remarkably, inspection of Fig. 2 shows that none of the Earth analogues reach the Earth PEP value. The thermodynamic difference between Earth and Earth analogues is even more pronounced when comparing the free energy values going from TOI700-d with an available free energy value 15 per cent lower to Trappist-1 g

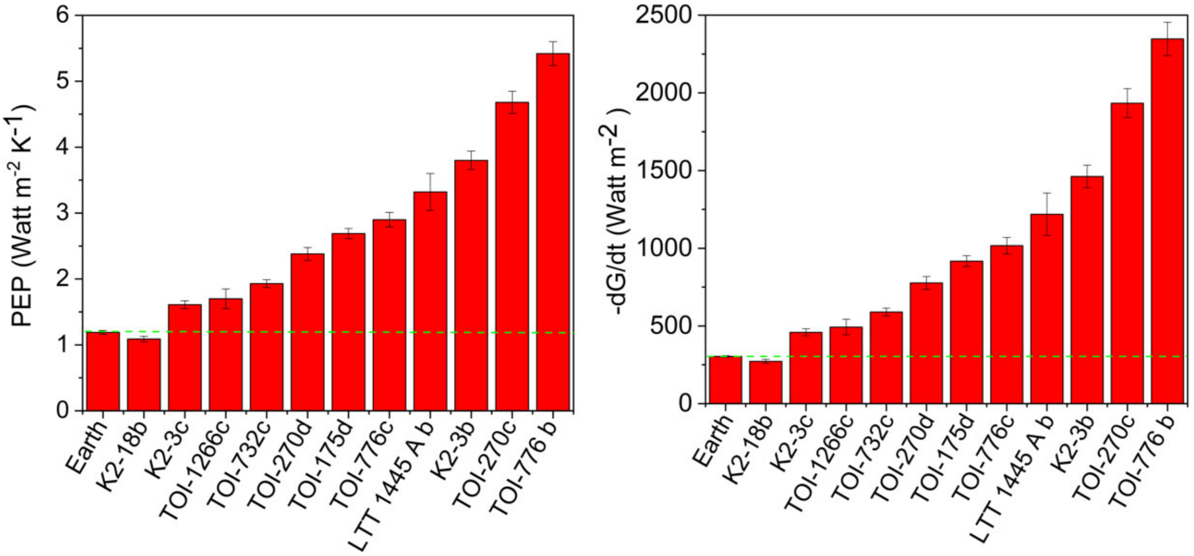

Figure 3. Planetary entropy production (left) and corresponding free energy (right) for known Hycean planets. The horizontal dotted line shows the corresponding Earth value.

which has a free energy value about 4-fold lower than the one of the Earth.

We then computed PEP and available free energy for several exoplanets belonging to recently proposed new class of habitable planets, the so-called ‘Hycean worlds’ (Madhusudhan et al., 2021). These planets are composed of water-rich interiors with massive oceans underlying H2-rich atmospheres and their habitable zone (HZ) can be significantly wider than the terrestrial-like HZ as liquid water can exist at much higher temperature up to 500 K. For our calculation the parameters for these planets were taken from the work of Madhusudhan et al. (2021). Fig. 3 shows the computed PEP and available free energy for a number of these Hycean worlds. Remarkably, with the exception of K2-18b, all the chosen Hycean worlds have much greater PEP and free energy than the Earth, reaching up to 8-fold (with TOI-776b) the available free energy of the Earth. Thus, from the thermodynamic point of view, the Hycean worlds could be more habitable than the terrestrial-like planet and can be good candidate for future observations in search of exoplanetary biosignatures.

4. CONCLUSIONS

The increasing rate of exoplanets discovery around nearby stars call for additional criteria useful to rank their habitability and in prioritizing target selection for extended observational campaign. In this frame, we focus on the entropy production, a thermodynamic function crucial in the framework of non-equilibrium thermodynamics. We propose that the PEP can be a good indicator of the propensity of a planet to host life for several reasons. The first one is that life is a natural process and thus need to produce entropy over evolutionary time without reaching the thermodynamic equilibrium. The second one is that the extent of entropy production is strongly related to the formation and evolution of complex systems as shown by the non-linear thermodynamics of the irreversible processes. The extent of entropy production (and thus of dissipation rate) is a measure of the distance of the system from the thermodynamic equilibrium. To be far-from equilibrium is a necessary condition for the emergence of complex phenomena and generally increasing the distance from equilibrium leads to an increase in the system complexity. The key point is that dissipation is what drives the emergence and sustains such self-organizing processes within the system (such as the ones involved in climate system and biosphere). In other words, dissipation is the prize for the origin and evolution of complexity, it is the coin to pay for complexity. Higher dissipation is usually associated with higher complexity in the resulting spazio-temporal structures (Ulanowicz & Hannon 1987; Lloyd & Pagels 1988). Here on Earth, fossil records seem to support this hypothesis showing evidence of growing complexity of life forms over time corresponding to growing dissipation (Zotin et al. 2001). Further, it has been suggested that the timing and mode of the observed biological evolution can be well rationalized within the framework of the thermodynamics of far from equilibrium systems (Gould & Eldredge 1977; Schneider & Kay 1994; Davies 2004). A third reason that makes PEP a good marker of the planetary potential to host a biosphere is that it is related to the potential of the planetary climate system to sustain efficient geophysical nutrients recycling mechanisms (Schulze-Makuch et al. 2020; Kleidon 2021). This ability is related to the extent of motion (atmospheric and/or oceanic) within the systems and thus to the dissipation rate. This is relevant as it has been suggested that the rate of nutrients cycling is the limiting factor to the growth of the biosphere rather than the availability of light (Covone et al. 2021; Kleidon 2021). In a habitable planet, the climate systems should be active enough to allow the transport and exchange of nutrients between the living organisms and their environment. For example, here on Earth, nutrients availability for marine life is related to ocean mixing and upwelling of deep-ocean water which are reach of nutrients. A more habitable planet than the Earth should be a planet characterized by a greater ability to exchange matter between the biosphere and the environment thus supporting more biomass and biodiversity (see e.g. Schulze-Makuch et al. 2020). In this frame, a first order estimate of the potential of planetary environment to generate motion and to sustain life is thus closely related to the PEP value which measures the vitality of the whole climate system. Definitely, this potential to be realized, need an adequately dense active fluid (the planet atmosphere) able to transform the stellar radiation energy in kinetic energy. Nevertheless, the availability of a negative entropy flow remains a necessary condition for the existence of such transport mechanisms. To note that the production entropy due to the thermal conversion of the radiation is by far the larger contribution to the PEP in comparison with the contributions due to the climate processes and biosphere. However, the free energy dissipated in this process is not useless but contributes to the achievement of that dissipation threshold necessary for the establishment of complex phenomena involved in the climate system, somehow linking the entropy produced in the thermalization of radiation process to the whole biosphere origin and evolution. In other words, the climate processes sustaining the whole biosphere originate at the expense of the enormous dissipation price paid with the thermalization of stellar free energy (reflected in the PEP value). All these reasons suggest that PEP could be a basic, first approximation tool for thermodynamically grading exoplanets to be used in conjunction with more conventional habitability indexes.

Prompted by these considerations, we employed a simple model to compute the PEP rate in steady-state conditions as function of stellar temperature and planet orbital parameters. The obtained value is an upper limit as it assumes steady-state conditions and it does not consider any attenuation due to atmosphere radiation absorption or diffusion. Certainly, the available entropy (at the planetary surface) is lower when absorption and re-emission of the stellar radiation by the planet atmosphere is considered. Nevertheless, our approach has the advantage that it does not depend on the additional assumptions on the details of the planetary atmospheric composition and structure that are commonly unknown and not easily predictable (Elkins-Tanton & Seager 2008). Our results show that both PEP and the available free energy for Earth-like planets increase with stellar temperature and that there are large differences between the inner and outer edge of the CHZ. From the thermodynamic point of view, the inner edge of CHZ is more favourable to the development of a biosphere as it corresponds to higher PEP and free energy values at each stellar temperature. Interestingly our planet is just in the right place to have the higher PEP possible within the Sun's CHZ (i.e. close to the inner edge) reinforcing the hypothesis that PEP has to play a role in the life emergence and evolution. Assuming that Earth PEP value is a necessary condition for life, we could define an 'entropic habitable zone' (EHZ) as the distance from a star where both liquid water and a PEP value $\geq$ Earth's value can occur. In this hypothesis, EHZ results to be a small fraction of the classical CHZ around G and F stars whereas M and K stars cannot sustain Earth-like PEP remaining within their CHZ. These results suggest that exoplanet around low-mass stars could not develop life and/or sustain an Earth-like biosphere. To note that similar conclusions have been reached by other authors starting from different point of views and with a more sophisticated approaches involving additional hypotheses (Ranjan et al. 2017; Haqq-Misra 2019; Lingam & Loeb 2019; Covone et al. 2021). Interestingly, we found that recently proposed habitable Hycean planets show PEP much greater than the Earth suggesting that they could potentially host biosphere greater (a maybe much complex) than the Earth's and thus, can be more habitable worlds than the Earth analogues. In the near future the search of biosignatures in these types of planets can be a way to test the reliability of PEP as index for habitability.

Finally, we like to emphasize an additional reason that makes PEP appealing as an indicator of planet habitability: it makes no assumptions about the underlying biochemistry of the alien life. It is a 'universal' need for any form of life, a necessary condition to develop a biosphere on a planet. Other planets could harbour forms of life unknown to us that could 'live' under physicochemical conditions very different from Earth (Benner et al., 2004). Several speculations have been made on forms of life based on a different chemistry and solvent and there will be always uncertainties about which physical–chemical conditions are indispensable for life (Benner et al. 2004; Schulze-Makuch et al. 2015). One thing is certain: the second law of thermodynamics is universal and unquestionable and must be fulfilled by any forms of life.

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DATA AVAILABILITY

No new data were generated or analysed in support of this research. All data employed in this work were obtained from the cited literature.

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