Article

Perspectives on the Origin of Life in Exoplanets as a Phenomenon Generated by a 3D Quantum Vacuum

Davide Fiscaletti[*]

SpaceLife Institute, Italy

Abstract

A model of the origin of life in exoplanets as a phenomenon generated by a quantum potential of a three-dimensional quantum vacuum acting as a reservoir of heat is proposed, which implies that the probability of life in exoplanets is determined by the heat that describes the interaction between the living organism and its environment, the surface temperature of the planet and the fluctuations of the quantum vacuum energy density in the region into consideration. It is shown how, in this picture, not only the parameters of the planet and the star influence the habitability of a planet and the duration of the habitability, but also a quantum term associated with the action of the quantum potential of the vacuum which implies that life is a global non-local property which can transmit instantaneously from a region to another of the universe.

Keywords: Origin of life, exoplanet, 3D quantum vacuum, quantum potential, non-local propery.

1. Introduction

For several decades, researchers have been studying exoplanets, including the so-called Earth-like planets, rocky planets with a radius between 1 and 1.75 times that of the Earth and whose orbit is located within the habitability zone of a similar star to the Sun, at a distance compatible with the presence of liquid water on the planet's surface. Since the discovery of the planet 51 Pegasi b orbiting a solar-type star in 1995, several exoplanets have been discovered. Today, the number of confirmed exoplanets is about 4000 with over 600 planetary systems possessing more than one exoplanet and among them there are several Earth-like exoplanets. The search for exoplanets today certainly represents one of the most advanced frontiers of astrophysics, which stimulates scientists to use their resources in order to find biosignatures as well as technosignatures, in order to answer two crucial questions that humanity has been asking for millennia, namely "Are we alone in the universe?" and "What is the origin of life?".

Habitability of an exoplanet can be defined as the potential of an environment (past or present) to support life of any kind and is thus a function of a multitude of environmental parameters whose study is influenced by the effects that biology has on these parameters. Despite the immense difficulties and challenges one has to face as regards the problem of identifying extraterrestrial life, the simplest way to treat this topic remains to search for "life as we know it" on a planet that shares the basic physical properties of the Earth. Water is conventionally regarded as one of the most essential requirements for

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[*] Correspondence: Davide Fiscaletti, SpaceLife Institute, San Lorenzo in Campo (PU), Italy. E-mail: spacelife.institute@gmail.com
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life on Earth by virtue of its unusual physicochemical properties [1]. As a consequence, many studies tend to adopt a "follow the water" approach, namely to search for planets where liquid water could exist on their surfaces. Since the pionieristic works of Hart [2, 3] till the more recent ones by Kasting et al. [4] and Kopparapu et al. [5], this "surface liquid water" criterion has been used to define the Habitable Zone as that range of distances from a parent star in which an Earth-like planet could maintain liquid water on its surface and so potentially host a surface biosphere. Although subsurface liquid water is entirely possible and may even be common — as suggested by the interior oceans of the icy moons in our Solar System — detecting that water, and any subsurface biosphere supported by it, is very difficult with remote-sensing telescopic observations. Consequently, the search for habitability and life on exoplanets will focus on telescopic observations of planetary atmospheres and surfaces, where a surface biosphere will be more apparent. In fact, another important condition which must be satisfied in order to guarantee the possibility of a planet to host life lies in the fact that the planet needs to retain an atmosphere since water ice transforms directly into gas phase in vacuum.

On the basis of our current knowledge, one can utilize the term "habitable zone" in order to identify the region around a star where an orbiting planet has the highest probability of being detectably habitable, for remote-sensing studies. Although we do not currently have a means of observing markers of surface habitability on exoplanets, these capabilities are expected in the near future.

On the other hand, the habitable zone of a planet depends not only on stellar properties but also a wide range of planetary properties. As the field of astrobiology develops, it is becoming clearer that multiple factors, characteristics and processes, can impact whether a planet can acquire and maintain liquid water on its surface. These include the properties of the planet (such as atmospheric composition, atmospheric escape/retention, volatile inventory and delivery, cycling of elements between surface and interior, planetary magnetic field, planet mass and size), star (which can include: stellar spectral energy distribution, activity, stellar winds, age, X-ray/ultraviolet emission, magnetic field, and stellar multiplicity) as well as planetary system (in particular, orbital architecture of planets in the system and the presence of giant planets), and how these factors interact over time [6].

As regards the planet's environment, its mass, radius, orbit, interior, surface and atmosphere are elements that affect its habitability. Once life has evolved on a habitable world, it becomes a planetary process that can also impact its environment [7-10]. 1.5 $R_{\odot}$ radii is the upper limit for an exoplanet to be more likely to have a predominantly rocky composition [11-13]. A planet's mass impacts planetary habitability in multiple ways, by providing radiogenic heating from long-lived radionuclides to drive internal heating and tectonics [14] as well as generation of a magnetic field [15], which is a key parameter that determines atmospheric retention [16-18]. Planetary mass, via planetary gravity, also rules atmospheric scale height, which can modify the rate the planet radiates to space, as well as its climate and the limits of the habitable zone [19]. The planetary orbital parameters, such as semi-major axis, eccentricity, obliquity, and rotation rate, affect planetary habitability through their control on the stellar radiation received by a planet over its orbit, and associated feedbacks on the climate system.

An active and dynamic interior plays a crucial role in determining the habitability of a planet, by driving the generation of a magnetic field [20, 21] and outgassing [22], which are key factors in order to produce and maintain a secondary atmosphere. Magnetic fields are another important factor when considering the habitability of a planet, since they may protect planets from losing volatiles (such as water) through stellar wind interactions [16, 23, 17, 21, 24, 25], even if recent studies suggest that there is a complex relationship between magnetic field and atmospheric escape, in terms also of the strength of the planet's intrinsic magnetic field and the incoming stellar wind pressure [18].

On the other hand, the host star's features have a huge influence on a planet's environment and habitability. Stellar mass and radius determine many of the star's fundamental characteristics, such as temperature and lifetime. Stellar luminosity evolution drives strong climate change and may result in atmospheric or ocean loss, which is a compositional change and often a threat to habitability. The stellar spectrum and activity levels influence atmospheric escape and climate, provide the most abundant surface energy source for the majority of planets of the habitable zone, and photochemically modify the planet's atmospheric composition.

Moreover, also the interactions among the planet, its host star, and its planetary system constitute another category of factors that in part determine whether a planet is and can remain habitable. Radiative interactions with the host star can modify planetary atmospheric compositions by driving the photochemical production of aerosols or gas species. These modifications of the atmosphere subsequently affect planetary climate and the ultraviolet flux incident at the planet's surface, both of which directly affect habitability. Gravitational interactions between the host star, planet and the planetary system can modify orbital properties which in turn modulate insolation levels and therefore climate. Gravitational interactions also may be responsible for late volatile deliveries from comets deflected into the inner part of stellar systems. Tidal interactions between bodies in the system can influence planetary interiors, ruling the magnetic dynamo and plate tectonics, both of which play significant roles in the maintenance and retention of secondary atmospheres on terrestrial planets.

The characteristics and processes which play a relevant role regarding the maintenance of surface liquid water on a terrestrial planet are broad, interdisciplinary and interconnected, and both theoretical modelling and astronomical observations will be needed to understand them. At this time, our best first-order assessment method for establishing whether or not a planet is likely to be habitable has been to check whether a newly discovered exoplanet is in the size range that is likely to be terrestrial, and is in the habitable zone of its parent star. As we have said before, in the light of our current knowledge, we can say that habitability is maintained via the interplay of the planet, of the stellar and planetary system characteristics over the planet's lifetime. In particular, within this new framework, R.K. Kopparapu, E.T. Wolf and V.S. Meadows have recently suggested that the habitable zone of a planetary system can be seen as a 2-dimensional slice in stellar type and semi-major axis through a multi-dimensional parameter space, that understanding how the balance between outgassing and atmospheric escape sculpts the resulting terrestrial planet atmosphere, and potentially replenishes an ocean, will be an important new frontier in terrestrial exoplanet evolution and habitability and that an interdisciplinary system science approach will be needed to fully explore the depth and complexity of planetary habitability [26].

As regards the problem of determining the habitability of a exoplanet, by considering the detection of biosignatures (or technosignatures) on an Earth-like planet (a planet with basic physical parameters similar to Earth) orbiting (i) an arbitrary star with a general mass M_*, and (ii) a G-type star of approximately solar mass $M_\oplus$, in the recent paper "Optimal target stars in the search for life" Lingam and Loeb estimated the probability to find life in a given planet with the parameter:

$$B \propto PP \tag{1}$$

where P denotes denotes the probability that the chosen planet has life, and P is the probability that the biosignatures arising from this exolife are detectable. Moreover, they compared the relative benefits of the strategies (i) and (ii) through the variable:

$$\Delta = \frac{B_\star}{B_\odot} = \left(\frac{P_\star}{P_\odot}\right)\left(\frac{\mathrm{P}_\star}{\mathrm{P}_\odot}\right) \qquad (2)$$

From (2) it derives that the value of Δ depends on the ratio:

$$\mu = \frac{P_\star}{P_\odot} \qquad (3)$$

which quantifies the ratio of the probabilities of life-bearing planets around stars of mass M_* and $M_\odot$. In order to provide an estimate of the value of μ, which can be interpreted as the relative likelihood of life in a given planet, the most common procedure is to utilize physical constraints on habitability regarding bioactive ultraviolet radiation, magnetic fields, planetary magnetospheres, atmospheric erosion, water loss, which according to recent studies seem to indicate that life-bearing planets around M-dwarfs are likely to be rare with respect to Sun-like stars [27, 4, 28-30]. However, if one considers atmospheric escape driven by the stellar wind [31] as well other constraints (e.g. stellar ultraviolet radiation and lifetime) which can be incorporated in a similar fashion [32], the relative likelihood of life may be expressed as:

$$\mu \approx \left(\frac{L_\star}{L_\odot}\right)\left(\frac{\mathrm{M}_\star}{\mathrm{M}_\odot}\right) \qquad (4)$$

where L denote the corresponding luminosity of the planet.

In this paper our purpose is to suggest new scenarios as regards the estimate and interpretation of the quantity (3), introduced by Lingam and Loeb in order to evaluate the likelihood of life in a planet, inside a model of a three-dimensional quantum vacuum defined by RS processes of creation/annihilation of virtual particles occurring in correspondence to elementary energy density fluctuations. This paper is structured in the following way. In chapter 2 we will show in what sense the origin of life in an exoplanet is determined by a quantum potential of the three-dimensional quantum vacuum. In chapter 3 we will compute the probability of life in an exoplanet inside our model. Finally, in chapter 4 we summarize the results of the paper underlining the perspectives of our model.

2. On the role of the quantum potential of the vacuum in the origin of life in a planet

Our uncertainty about the origin of life can be associated with our ignorance in calculating the probability, for matter, to give place to a transition from non-living to living state. The knowledge of this parameter is important not only for understanding life on Earth, but also for estimating the distribution of life in the universe [33].

Today we have got a number of explicit models which provide clues regarding the emergence of life, and how the traditional tools of physics can help us to give a solution to this problem. However, we are far from a resolution to our question "How is it that life can emerge from non-living matter?". Most work on fundamental properties of life focuses on the concept of information [34, 35] which plays an important role for quantitative theories of life's origins too [36]. The mathematical relationship between Shannon and Boltzmann entropies suggests a potentially deep connection between information and thermodynamics [37]. This connection has been explored by substantial work over the last decade (see, for example, [38] for a recent review of this topic). On the other hand, Schrödinger was aware of the link between information and life in his considerations on biology, coining the term "negentropy" in order to describe life's ability to seemingly violate the 2nd law of thermodynamics. Yet, he still felt that something was missing and ultimately suggested the perspective that "other laws" might be necessary for the description of life [39].

Von Neumann was one of the first to consider the possibility that information plays a key role in living systems [40]. He recognized that one cannot explain the origin of the complexity of living systems (which he hoped to emulate in artificial systems), in terms only of the copying information (even with mutation and selection), but at this purpose the concept of constructability must additionally be introduced [41]. Copying and construction as introduced by von Neumann are two fundamentally different physical processes, although they may ultimately lead to the same effective result, namely the reproduction of information stored in one physical media in another. In the case of copying, the information is replicated from one media to another of the same physical stuff (or nearly so) [42]. Constructors by contrast perform transformations on physical objects, such that one physical media may be transformed into another.

The concept that living systems (and their artefacts) mediate transformations that do not violate known laws of physics, but are at the same time not predicted by them, may be considered as one of the most fundamental features of life, suggesting that an explanation for life does not lie in explaining the states themselves, but instead the paths [43]. This view is consistent with an emerging emphasis in nonequilibrium thermodynamics on trajectories rather than states.

Marletto has recently underlined that an important feature of life is that life not only copies information but also uses it to construct itself and can utilize information to construct other objects [44]. This implies that, if one wants to model the origin of life, the concept of life as "information that copies itself" must be intended in the sense that "simple machines that can make slightly more complicated machines" [45]. In other words, one has to invoke the existence of non-trivial replicators that process information in an active sense, enabling the system's dynamics to (in part) be directed by the current informational state ("program") of the system. This is the key idea which underlies the philosophical concept of top-down causation [36, 35, 46].

Living systems can be seen as embedded hierarchies, with complex flows of information between scales of organization [47] that do not generally permit this layer-by-layer decomposition of causation (information flows from 'higher' to 'lower' levels). That is, life could be regarded as a hierarchy of 'constructors', or at least information flows that mediate which transitions occur and when. It is widely recognized that the procedure of coarse-graining (which defines some of the relevant "informational" degrees of freedom) plays a foundational role in how biological systems are structured, by defining the biologically relevant macrostates [48]. However, it is not clear how those macrostates arise, if they are objective or subjective [49], or whether they are in fact a fundamental aspect of biological organization.

The emergence of life can be re-stated as a problem of explaining how (biological) hierarchies emerge (these should be distinguished, for example, from re-normalization group flows or other 'hierarchies' in physics, since in biology the individual 'levels' are not self-similar). The mechanisms through which topdown causation, if indeed it is a real and not just apparent property of nature, could operate in biology would most likely be through information (in an as yet unspecified manner) acting as a causal agent. The idea of information is itself abstract, but it must be emphasized that each bit of information is instantiated in physical degrees of freedom: "information is physical!", if we want to use an icastic sentence of Rolf Landauer [50]. Whether fundamental or an epiphenomenon, the causal role of information in biology represents indeed one of the hardest explanatory problems for solving the origins of life.

In [36] Walker and Davies presented a framework for understanding the origin of life as a transition in causal structure, and information management and control, whereby information gains causal efficacy over the matter it is instantiated in. The Walker and Davies approach suggests that a rigorous distinction between life and non-life is most likely to derive from the distinctive mode of information management and control displayed by living systems. While both the traditional digital-first and analogue-first viewpoints neglect the active (algorithmic or instructional) and distributed nature of biological information, in the Walker and Davies model, the real challenge of life's origin is to explain how instructional information control systems emerge naturally and spontaneously from mere molecular dynamics and the key distinction between the origin of life and other 'emergent' transitions is the onset of distributed information control, enabling context-dependent causation, where an abstract and non-physical systemic entity (algorithmic information) effectively becomes a causal agent capable of manipulating its material substrate [46, 51].

The advantage of this perspective is that it provides a foundation for identifying the origin of life as a well-defined transition, by shifting emphasis to the origins of information control, rather than, for example, the onset of Darwinian evolution or the appearance of autocatalytic sets. Walker's and Davies' approach also permits a broader view of life, where the same underlying principles would permit understanding of living systems instantiated in different chemical substrates (including potentially nonorganic substrates). But, how does this transition occur? What does it explain the distributed nature of biological information in living systems, where information gains causal efficacy over the matter it is instantiated in?

While in Walker's and Davies' approach this transition shift in the efficacy of information gaining of living systems over matter remains an open question, the model of the there-dimensional (3D) quantum vacuum developed by the author in several papers [52-55] has the merit to introduce interesting perspectives about these issues. In particular, here a starting-point consideration is that processing systems with delocalized information are evolutionarily robust, in other words that there exists a delocalized information in the form of a non-local connection between living systems and the elementary vibratory states of the 3D quantum vacuum.

Let us review briefly, before all, the essential features and results of the model of the 3D quantum vacuum. In the model proposed by the author in [52-55], all the events of our everyday life are the explicit manifestations of more elementary processes of a fundamental, deep arena, a three-dimensional (3D) timeless non-local quantum vacuum characterized by RS processes of creation/annihilation of virtual particles corresponding to opportune fluctuations of the quantum vacuum energy density. In this model, each material particle, which is revealed in the experiments, is associated to a specific excited state of the 3D quantum vacuum characterized by a diminishing of the quantum vacuum energy density $\Delta\rho_{qvE}=(\rho_{PE}-\rho_{qvE})$ and corresponding to opportune elementary RS processes of creation/annihilation of virtual particles, where the Planck energy density:

$$\rho_{PE}=\frac{m_p\cdot c^2}{l_p^3} \tag{5}$$

defines the ground state of the vacuum and

$$\rho_{qvE}=\rho_{PE}-\frac{m\cdot c^2}{V} \tag{6}$$

is the energy density of quantum vacuum inside the particle, m_P is Planck's mass, c is the light speed and l_p is Planck's length. Here, the RS processes of creation/annihilation of the virtual particles of the medium, which give rise to the appearance of a material particle of mass obtained from equation (6), can be described by a wave function $C=\begin{pmatrix}\psi\\ \phi\end{pmatrix}$ at two components satisfying a time-symmetric extension of the Klein-Gordon quantum relativistic equation:

$$\begin{pmatrix}H & 0\\ 0 & -H\end{pmatrix}C=0 \tag{7}$$

where $H=\left(-\hbar^2\partial^\mu\partial_\mu+\frac{V^2}{c^2}\left(\Delta\rho_{qvE}\right)^2\right)$. Equation (7) may be considered as the fundamental equation ruling the behaviour of the excited states of the 3D quantum vacuum. The crucial feature of the 3D quantum vacuum lies in its non-local character, which is associated with a quantum potential of the vacuum of the form:

$$Q_{Q,i}=\frac{\hbar^2c^2}{V^2\left(\Delta\rho_{qvE}\right)^2}\left(\frac{\left(\nabla^2-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\left|\psi_{Q,i}\right|}{\left|\psi_{Q,i}\right|}-\frac{\left(\nabla^2-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\left|\phi_{Q,i}\right|}{\left|\phi_{Q,i}\right|}\right) \tag{8}$$

The quantum potential of the vacuum (8) is the fundamental entity which the guides, in a non-local way, the occurring of the processes of creation or annihilation in space.

In the light of the results obtained in [56], the non-local information encoded in the 3D quantum vacuum is a crucial element which explains the origin of life, which explains the distinctive features of living systems, providing a rigorous distinction between life and non-life at a fundamental level. In this regard, the key element is represented by a quantum potential of the vacuum which has the role of generating an additional density of physical space in a living system. In other words, a quantum interaction between a living organism with its environment is generated which is determined by a quantum potential of the vacuum that acts as a heat reservoir, and this quantum potential of the vacuum acting as a heat reservoir produces an "additional density" of physical space in a living organism (living matter) with respect to inert matter. The quantum potential of the vacuum acting as a reservoir heat that is responsible for the origin of life in a planet, in the relativistic domain, is expressed by equation:

$$Q = \frac{\hbar^2 c^2}{V^2 \left(\Delta\rho_{qvE}\right)^2} \frac{\nabla^2 Q_{hf}}{\hbar\omega} \tag{9}$$

while in the non-relativistic domain is:

$$Q = -\frac{\hbar^2 c^2}{2V \Delta\rho_{qvE}} \frac{\nabla^2 Q_{hf}}{\hbar\omega} \tag{10}$$

where $\hbar\omega/2$ is the average kinetic energy associated with the vibratory states of the 3D quantum vacuum and ΔQ_{hf} is the heat that describes and regards the interaction between the living organism and its environment.

By following Grössing's thermodynamic approach to the quantum potential [57, 58], in our approach of a 3D non-local quantum vacuum as fundamental origin of physical processes, the quantum potential of the 3D quantum vacuum which rules the interaction between a living organism and its environment acts as a heat reservoir, as a thermal energy in the sense that generates the appearance of bio-photons which act non-locally in the environment itself. The instantaneous action of the bio-photons produced by the thermalized quantum potential of the vacuum implies that the distributions of the vibratory states in the environment under consideration contribute in their totality to the form of the heat distribution in the overall system and thus to the evolution of the living organism, leading to a promising perspective for a deeper understanding, in a global picture, of the origin of life in the universe. In other words, in our approach, we can say that the distributed nature of biological information in living systems, where information gains causal efficacy over the matter it is instantiated in, is determined just by the action of the quantum potential of the 3D quantum vacuum as a heat reservoir, that generates the appearance of bio-photons which act non-locally in the environment itself.

We can therefore give the following answer as regards the transition in the causal structure, as regards the ability of information management and control, the origins of information control, inside living systems: these elements, which are distinctive of living systems, are generated just by the fact that the quantum potential of the vacuum, acting as a heat reservoir, produces an "additional density" of physical space in a living organism with respect to inert matter. The action of the quantum potential of the vacuum as a thermal energy which generates the appearance of bio-photons which act non-locally in the environment, explains in what sense information plays a key role in living systems, in what sense living systems are characterized by complex flows of information between scales of organization, in what sense life may be regarded as a hierarchy of 'constructors', or at least as information flows that mediate which transitions occur and when. The key of explanation of all these informational processes characterizing living systems lies in the quantum potential of the vacuum.

Now, a fundamental consequence of this model is that the non-local action of the quantum potential of the vacuum makes life as a property that ultimately has a global feature, namely acts non-locally itself.

In other words, we can say that, in the light of the quantum potential of the vacuum (27) (or (26)), life is a property of all universe, is a cosmic property.

The non-local features of life may also be characterized by introducing an appropriate Bell length associated with the quantum potential of the vacuum (9):

$$L_{Bell} = \sqrt{\frac{\hbar^2 c^2}{2\Delta\rho_{qvE} V Q}} \tag{11}$$

namely,

$$L_{Bell} = \sqrt{-\frac{c\hbar\omega}{\nabla^2 Q_{hf}}} \tag{12}$$

namely, taking account of (9):

$$L_{Bell} = \sqrt{-\frac{2c\Delta\rho_{qvE} V}{\mathrm{n}\nabla^2 Q_{hf}}} \tag{13}$$

The condition $Q = 0$, i.e. $L_{Bell} = \infty$ provide the points where the action of the 3D quantum vacuum acting as a heat reservoir expressing the interaction between a living organism and its environment, namely where the additional density of physical space present in living matter, is delocalized, thus implying the evolution of life and equation (30) shows that this happens when:

$$\left|2c\Delta\rho_{qvE} V\right| \geq \left|\mathrm{n}\nabla^2 Q_{hf}\right| \tag{14}$$

Equation (14) is a plausible physical condition which, for a great number of RS processes of creation/annihilation of quanta corresponding to a great number n of virtual particles/antiparticles of the vacuum, practically occurs in a specific macroscopic volume V. This means in other words that the propagation of life in the universe, owed to the action of the thermalized quantum vacuum which functions as a heat reservoir, as a thermal energy which appear then as bio-photons which act non-locally in the environment itself, occurs instantaneously in all the points of the universe, namely that life is indeed a global property which is able to transmit itself in the entire universe.

Moreover, other relevant considerations may be made by taking account of the Metabolic Theory of Ecology. In the picture of the Metabolic Theory of Ecology several ecological parameters – such as the production and turnover of biomass, the rates of genetic divergence and speciation, species diversity and coexistence – are determined by the metabolic rate B of organisms given by:

$$B \propto m^{3/4} exp\left(-\frac{E}{k_B T}\right) \tag{15}$$

where m is the mass of the organism, k_B is the Boltzmann constant, T is the absolute temperature and E is the average activation energy which is associated to the appropriate rate-limiting step in metabolism [59]. Therefore, since here the activation energy E associated with the metabolism in a planet is ultimately generated the quantum potential of the vacuum acting as a reservoir heat which supports the interaction between the living organism and its environment, equation (15) can be opportunely expressed as:

$$B \propto \left(\frac{\Delta\rho_{qvE}V}{c^2}\right)^{3/4} exp\left(\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{k_B T}\right) \tag{16}$$

As a consequence, taking account that for life as we know it in our planet, the Earth-referenced temperature-dependent likelihood function”

$$P_T = exp[-26{,}7(\delta - 1)]\theta(T - T_L)\theta(T_U - T) \tag{17}$$

(where θ is the Heaviside function which assures that the likelihood becomes for $T < T_L$ and $T > T_U$, T_U and T_L are the limits over which the Boltzmann factor is valid and the temperature range $T_L < T < T_U$ is not expected to exceed the Earth-based photosynthesis limits for life-as-we-know-it) holds, and that the auxiliary parameter δ in equation (17) is expressed by relation:

$$\delta = \frac{E}{E_\oplus}\frac{T_\oplus}{T} \sim \frac{T_\oplus}{T} \tag{18}$$

where $E_\oplus = 0{,}66eV$ and $T_\oplus = 287K$ are the corresponding values for the Earth, and here $E \sim E_\oplus$, one obtains the following condition for the quantum potential of the vacuum as a reservoir heat relative to the parameters of the planet Earth:

$$\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{k_B T} = 26{,}7\left(\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{E_\oplus}\frac{T_\oplus}{T} + 1\right) \qquad 19)$$

Namely,

$$\nabla^2 Q_{hf} = \frac{2V\Delta\rho_{qvE}\omega E_\oplus k_B T}{\hbar c^2 E_\oplus - 26{,}7\hbar c^2 k_B T_\oplus} \tag{20}$$

which expresses the link between the heat $\nabla^2 Q_{hf}$ that describes and regards the interaction between the living organism and its environment, the surface temperature of the planet and the fluctuations of the quantum vacuum energy density in the region into consideration. An interesting advantage of equation (20) is that it reproduces correctly the fact that “origin of life”-type events are determined by the parameters of the surrounding environment and not necessarily by the global properties (such as the global temperature) of the planet.

3. The role of the quantum potential of the vacuum with regards to the probability of life in exoplanets and the duration of habitability

In our approach, life in an exoplanet is produced by a thermalized vacuum acting as a reservoir of heat. In particular, taking account of the results obtained by Lingam and Loeb in [60], the likelihood function of life in exoplanets may be expressed through the following equations:

a) $$P = exp\left(\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{k_B T}\right)\theta(T-T_L)\theta(T_U-T)\left(\frac{P_S}{1atm}\right)\left(\frac{R_P}{R_\oplus}\right)\left(\frac{\langle F_{EUV}\rangle}{\langle F_\oplus\rangle}\right)^{-1} \quad (21)$$

if the lifetime of the planet's atmosphere is less than the timescale of atmospheric loss for unmagnetized planets, and

b) $$P = exp\left(\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{k_B T}\right)\theta(T-T_L)\theta(T_U-T)\left(\frac{P_S}{1atm}\right)\left(\frac{a}{1AU}\right)^2\left(\frac{R_P}{R_\oplus}\right)^{-1,7}\left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{-1} \quad (22)$$

if the lifetime of the planet's atmosphere is bigger than the timescale of atmospheric loss for unmagnetized planets. In equations (21) and (22), $P_S = \frac{gM_{atm}}{4\pi R_P^2}$ is the surface pressure of the atmosphere (M_{atm} is the mass of the atmosphere, R_P is the radius of the planet), $\langle F_{EUV}\rangle$ is the average extreme ultraviolet flux, $F_\oplus$ is the value of $\langle F_{EUV}\rangle$ for the Earth, $R_\oplus$ is the radius of the Earth, a is the semi-major axis of the planet, $\dot{M}_\star$ is the stellar mass loss rate, $\dot{M}_\odot$ is the Sun's mass loss rate. The advantage of the functions (21) and (22) lies in the fact that they allow us to determine the likelihood of a planet being conducive to life with respect to Earth in terms of parameters which are direct observables, or can be deduced indirectly, by means of numerical simulations (except for uncertainties concerning the surface pressure and the surface temperature).

As regards the approach based on equations (21) and (22), the crucial point is that, despite the presence of some terms that for a given exoplanet seem to provide values which differ with respect to those of Earth (as Lingam's and Loeb's research demonstrate), this does not necessarily mean that the exoplanet into consideration does not host life because the quantum term $exp\left(\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{k_B T}\right)$ associated with the quantum potential of the vacuum, as a consequence of its non-local action, makes life a non-local property which can originate also in that peculiar exoplanet. In other words, in this picture, one can say that the habitability of an exoplanet is determined by the synergy of different parameters: some parameters regarding the planet into consideration (such as its atmosphere) and its star, as well as the quantum term $exp\left(\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{k_B T}\right)$ associated with the quantum potential of the vacuum, which indicates the role of life as a global non-local phenomenon. Therefore, a suggestive perspective introduced by the approach based on equations (21) and (22) is that a given exoplanet will be habitable and thus will host life when the term $exp\left(\frac{\frac{\hbar^2 c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2 Q_{hf}}{\hbar\omega}}{k_B T}\right)$ prevails with respect to the other terms appearing in (21) and (22), in particular the Heaviside function, the surface pressure of the atmosphere, the average extreme ultraviolet flux and the stellar mass loss rate.

The considerations we have made here allow us now to throw new light as regards the probabilities of life-bearing planets around stars of mass M_* and $M_\odot$, in the sense that the likelihood function of life in exoplanets may be expressed through simple equations where the value of the parameter

$exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right)$ must be put in comparison with the other terms appearing in these equations. The quantity $\mu=\frac{P_\star}{P_\odot}$, which represents the ratio of the probabilities of life in exoplanets around stars of mass M_* with respect to Earth, can be expressed through the following equations:

$$\text{a)}\quad \mu=\frac{exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right)\left(\frac{P_S}{1atm}\right)\left(\frac{R_P}{R_\oplus}\right)\left(\frac{\langle F_{EUV}\rangle}{\langle F_\oplus\rangle}\right)^{-1}}{exp[-26{,}7(\delta-1)]} \tag{23}$$

if the lifetime of the planet's atmosphere is less than the timescale of atmospheric loss for unmagnetized planets, and through the following equation:

$$\text{b)}\quad \mu=\frac{exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right)\left(\frac{P_S}{1atm}\right)\left(\frac{a}{1AU}\right)^2\left(\frac{R_P}{R_\oplus}\right)^{-1{,}7}\left(\frac{\dot{M}_\star}{\dot{M}_\odot}\right)^{-1}}{exp[-26{,}7(\delta-1)]} \tag{24}$$

if the lifetime of the planet's atmosphere is bigger than the timescale of atmospheric loss for unmagnetized planets. Clearly, as regards the probability of life in an exoplanet – which can be expressed through equations (23) or (24) – one must take into account that the upper bound on the habitability of a planet is the stellar lifetime and that the maximum duration that the planet remains habitable is less than the stellar lifetime for a simple reason: the stellar luminosity increases over time, and the planet will eventually enter a runaway greenhouse phase and become uninhabitable (like Venus). Thus, the duration of habitability is essentially specified by the temporal extent of the continuously habitable zone. By using the knowledge about the inner and outer boundaries of the habitable zone in conjunction with stellar evolution models, one can estimate the total duration of time (t_{HZ}) that an Earth-analog will remain inside the habitable zone as a function of the stellar mass M_*. By following [61], one obtains:

$$t_{HZ}\approx 0{,}55t_\odot\left(\frac{M_*}{M_\odot}\right)^{-2}\quad \text{if}\quad M_*>M_\odot \tag{25}$$

$$t_{HZ}\approx 0{,}55t_\odot\left(\frac{M_*}{M_\odot}\right)^{-1}\quad \text{if}\quad 0{,}5M_\odot<M_*<M_\odot \tag{26}$$

$$t_{HZ}\approx 0{,}55t_\odot\left(\frac{M_*}{M_\odot}\right)^{-1{,}25}\quad \text{if}\quad M_*<0{,}5M_\odot \tag{27}$$

where $t_\odot\approx 10Gyr$ and $M_\odot$ is the solar mass. By analysing (25)-(27), it follows that low-mass stars are characterized by continuous habitable zones that last for a longer duration of time, which is along expected lines since they have longer main-sequence lifetimes [62, 63]. Now, in our approach of 3D quantum vacuum, the interesting perspective is opened that the total duration of habitability of a planet is itself determined by the synergy of the values of the parameters appearing in equations (21) and (22), namely the parameters regarding the planet into consideration (such as its atmosphere) and its star, as well as the quantum term $exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right)$ associated with the quantum potential of the vacuum. in other words, it is the evolution of the values of the parameters appearing in equations (21) and (22) which contribute to make a given exoplanet habitable or non-habitable and, therefore, influences the total duration of habitability of that exoplanet.

Finally, it must be emphasized that the quantum term $exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right)$ associated with the quantum potential of the vacuum and which makes life a global property which has the potential to transmit instantaneously from one region to another, allows us to throw new light also as regards the computation of the number of planets which host life in a given region of the universe. In this regard, in [64] Lingam and Loeb estimated the number of planets with life in a particular volume through relation:

$$\mathcal{N}_b = N_{sur} \cdot f_e \cdot f_l \tag{28}$$

where N_{sur} is the number of stars that can be covered by a state-of-the-art telescope like the JSWT, f_e is the fraction of "habitable" planets per star, and f_l is the probability that a "habitable" planet is actually inhabited. If in Lingam's and Loeb's approach, f_e is an unknown quantity since we do not currently know the list of necessary and sufficient criteria for habitability, in our approach things are different because life is a non-local global property generated by the action of the quantum potential of the 3D quantum vacuum as a heat reservoir and $exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right)$ is the fundamental term which is responsible of this. As a consequence, in our model of 3D quantum vacuum as origin of life in an exoplanet, the unknown coefficient f_e of Lingam's and Loeb's approach can be replaced with the term $exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right)$ which indeed makes life a global property which has the potential to emerge everywhere in the universe. Therefore, in our model the number of planets with life in a particular volume can be expressed through the following relation:

$$\mathcal{N}_b = N_{sur} \cdot exp\left(\frac{\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\frac{\nabla^2Q_{hf}}{\hbar\omega}}{k_BT}\right) \cdot f_l \tag{29}$$

In summary, equations (21), (22), (23) and (29) have the potential to determine relevant perspectives in order to explore the possibilities of life in the different exoplanets and different galaxies and stellar systems existing in the visible universe. These equations indeed introduce a field which is all to be explored. In this regard, further research will give you more information.

4. Conclusions and perspectives

In this paper, we have examined the likelihood function of life in exoplanets, we have estimated the number of planets with life in a given volume of the universe, and we have made considerations about the duration of the habitability of an exoplanet, in the context of a 3D quantum vacuum model where life is originated by the action of a quantum potential of the vacuum as a heat reservoir, thus providing an additional density of physical space in a living organism. The crucial result of this approach lies in the perspective that life is a non-local global property which has the potential to transmit instantaneously from one region to another and thus that the habitability of an exoplanet is determined not only by the parameters of the planet and of its star, but also depends on a quantum term associated with the action of the quantum potential of the vacuum as a heat reservoir, thus implying the idea that life is a global property.

The next step regards the computation of the probability of the development of intelligent species in a given region and thus the estimation of the number of technological extraterrestrial species. In this regard, in July 2015 a 10-year program has been announced, named Breakthrough Listen Initiative, which has the aim to quantify the distribution of advanced, technologically capable life in the universe [65-67]. Our model of 3D quantum vacuum has the potential to throw new light in this research regarding the number of technological species in the universe, compatibly with the idea that life elsewhere can have a non-carbon chemical foundation.

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