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From Stars to Cells: The Search for Life Through the Cosmic Life Viability Metric

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Abstract: *Traditional models, such as the Drake Equation, offer expansive and sophisticated estimates for the existence of extraterrestrial life; however, they lack a detailed integration of stellar and planetary conditions and remain beyond the current scope of scientific capability. This paper introduces the Cosmic Life Viability Metric (CLVM), a probabilistic model that synthesizes astrophysical and planetary factors to assess the likelihood of life in exoplanetary systems, with a particular focus on G, K, and M-type stars. The CLVM incorporates variables such as spectral type, habitability, stellar age, temperature stability, atmospheric suitability, and bioavailability, alongside a unique term Ψ, which accounts for unknown or poorly understood scientific domains that may influence the potential for life. The model has been applied to two systems: the Sun-Earth system, which demonstrated a high viability score (~97.5%), and the K2-18 system, an M-type star, which, despite being a leading candidate among exoplanets, exhibited a viability score of (~26.2%), suggesting limited habitability, potentially supporting microbial life beneath oceanic surfaces. Although some variables remain Earth-centric due to data limitations, the CLVM offers a physically grounded framework for identifying life-supporting systems for future observational missions.*

Key words: *Astrobiology, Cosmic Life Viability Metric, Drake equation, Exoplanets.*

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I. INTRODUCTION

The pursuit of extraterrestrial life has garnered significant attention in recent times. Understanding the planetary conditions conducive to life is a fundamental aspect of astrobiology. However, the Drake Equation, which has historically driven this search, is predicated on broad assumptions that are currently beyond our empirical reach. Consequently, there is a need for more physics-based models that integrate measurable properties. This paper introduces the Cosmic Life Viability Metric (CLVM), a probabilistic framework designed to assess the potential for life based on six critical parameters: the spectral type of the host star, planetary temperature suitability, atmospheric stability, stellar age, and biological resource availability and habitability conditions. The model incorporates established astrophysical thresholds and employs a logical switch function to regulate viability estimates. Rather than offering speculative estimates of civilizations, the CLVM emphasizes the life-supporting potential at the system level. It is applied to the Earth–Sun system and the exoplanet K218b to illustrate how empirical data can inform habitability assessments in a structured, quantitative manner. The model is adaptable for application across various stellar types and planetary environments and can be updated as new observational data become available. This approach provides a practical method for prioritizing targets in the ongoing search for habitable worlds. The objective is not to predict the existence of life but to quantify where life is most likely to occur. The CLVM represents a significant advancement in developing testable, data-driven tools within the field of astrobiology.

II. STELLAR CLASSIFICATION

Stars that were a wonder and always been a point of interest are now explored through their electromagnetic spectra. The spectral lines reveal the abundance of elements and other important properties. Stellar classification plays a crucial role in understanding the chemical and physical properties of stars [1]. Understanding stellar classification is essential for examining planetary system formation and assessing life-hosting potential [2]. The stars are categorized using the Morgan-Keen (MK) classification system. In this system, stars are classified based on their spectral characteristics [1]. Stars are classified into seven types: O, B, A, F, G, K, and M. The sequence reflects decreasing stellar surface temperatures, with O-type stars at the hottest end and M-type stars at the coolest [1]. Each spectral class is subdivided into numerical subclasses ranging from 0 (indicating the hottest stars) to 9 (the coolest). In addition to this classification, MK systems also have a luminosity class represented in Roman numerals. where O is for hypergiants, I is for supergiants, II is for bright giants, III is for giants, IV is for subgiants, V is for main-sequence stars, VI is for subdwarfs, and VII is for white dwarfs [1]. The MK system allows for individual classifications, whereas the Hertzsprung–Russell (HR) diagram provides a detailed graphical representation of stellar evolution by plotting each type of star in a luminosity-effective temperature graph [1]. Among all stellar types, G, K, and M-type stars are the most promising candidates to host life beyond our solar system or even beyond our galaxy due to their stability and positive radiation output [3], [4]. Despite being abundant, M-type stars lack high temperatures and luminosities, which makes them a bit difficult to find in the vast universe. Their unstable radiation output and frequent flaring are not that good indications, making the probability of finding life a bit hard, and if life exists there, it can be considered as a mixture of cosmic luck and highly habitable conditions [4], [5]. It's important to remember that not all stars have planetary systems, and even those that do may not have planets in the habitable zone. Moreover, not every planet located in a habitable zone will necessarily support life [3]. When compared to the number of stars present in our universe, this issue vanishes, giving the hope that we have some other beings sharing the same universe. Remember, not only stellar characters but also perfect planetary conditions are needed for life to form and flourish [2], [4]. Let us understand the physical relations in stellar systems through the next paragraph.

III. PHYSICAL RELATIONS IN STELLAR SYSTEMS

The structural & energetic properties of main sequence stars are often fundamentally governed by their mass, with interdependent relations between stellar mass, radius, and luminosity forming the backbone of stellar astrophysics. The (M-R-L) mass-radius-luminosity relations do vary across spectral types. Particularly among G, K, & M types, which make up ~90% of the stellar population in our Milky Way galaxy [6]. The quantitative form of M-R-L relations can be expressed as: $L \ \alpha \ M^{\alpha}$ and $R \ \alpha \ M^{\beta}$, where α and β vary with mass and internal structure of the star [6], [7], [8].

From an astrobiological point of view, MRL relations are very much important for evaluating the habitability potential of exoplanets. We know that a star's luminosity directly determines the boundaries of its habitability zone. The mass-luminosity relation gives the estimation of where potentially life- supporting planets might exist [6]. The mass–radius relation informs planetary equilibrium temperature calculations by determining the star's total radiative output and surface area [6], [7]. Remember that a star's mass also sets its main sequence lifetime, maximizing the duration over which a planet can remain within its habitable zone [7], [8]. Highly massive stars leave the main sequence a lot earlier, before any biospheres could develop, while less massive stars stay in the main sequence for a lot more time and provide stable output, which might support conditions for life to form and flourish [8], [3]. Therefore, the MRL relations serve as critical input parameters in climate modeling, atmospheric photochemistry simulations, and biosignature detectability analyses for exoplanetary systems [3], [4]. These relations help us in prioritizing astrobiology-focused missions such as JWST, LUVOIR, and many more, ensuring that the search for extraterrestrial life is directed toward systems with the highest scientific potential [4].

STELLAR METALLICITY AND PLANETARY FORMATION

Stellar metallicity is an important factor that decides the frequency, and nature of planetary systems. It is defined as the proportion of elements heavier than hydrogen and helium and represented by the logarithmic ratio [Fe/H]. The metals include all elements beyond helium, such as iron, silicon, carbon, and oxygen, which are the foundation for the formation of planetary cores, rocky planets, and complex molecules. The metallicity of a star reflects the chemical composition of the protoplanetary disc from which it formed, directly hinting at the solid materials available for planet formation.

Metallicity decides planetary formation & also what kind of planets dominate in a given system. High-metallicity systems ([Fe/H] > 0) contain massive planets and gas giants, which can disturb the orbits of smaller terrestrial companions. They might be pushed inwards, away from the habitable zones. Whereas, stars with sub-solar metallicity ([Fe/H] < 0) may produce fewer giants, offering more stable environments for smaller & rocky planets to stay in the habitable zone. So, if we are searching for a better life-hosting planet, we are definitely looking for a better host star, and with this analysis we can figure out where to search. In G-type star systems there is a scope for gas giants to form; in K-type star systems the probability might change from system to system; and coming to M-type star systems, there is less chance of finding gas giants. Remember, low metallicity doesn't entirely preclude planetary formation. Terrestrial planets can still emerge around low-metallicity stars; if other disc conditions also support the formation, then the chances might increase [9].

HABITABILITY ZONE DYNAMICS

The habitability zone (HZ) concept has a special place in the heart of astrobiology & planetary science. The HZ is defined as the circumstellar region in which a rocky planet, with suitable atmospheric composition and pressure, could maintain water in a liquid state over geological timescales. The HZ dynamics are shaped by multifaceted interactions between stellar properties and planetary climate feedback mechanisms. The main factor in determining the habitability zone is the star's luminosity, which controls the radiative energy output available to orbiting planets [10]. Along with the increase in luminosity, mass, and effective temperature, the HZ moves outward. So, for cooler stars with lower luminosities, the HZs are much closer, and due to this reason, we observe tidally locked planets [11].

Stars of different spectral types emit energy in different wavelengths. M-type stars radiate in infrared, which has a different interaction with greenhouse gases compared to the visible output of G- and K- type stars. The variation alters how the energy is absorbed and re-radiated in a planet's atmosphere [12]. Atmospheric parameters such as surface pressure, cloud albedo, CO_2 concentration, and planetary rotation influence the width and stability of the HZ [13], [14]. Planets with carbon dioxide-rich atmospheres can extend the outer edge of the habitable zone thanks to their enhanced greenhouse warming, while those near the inner edge may be pushed into runaway greenhouse states if insolation exceeds their capacity for radiative cooling [10], [14].

The conclusion is that the HZ is not a perfectly set boundary; it is a dynamic region shaped by planetary conditions and stellar properties. While it offers a valuable filter in the search for life, true habitability depends on a complex set of factors that extend far beyond just distance from the star. Understanding these interactions is crucial as we continue to explore the diversity of exoplanetary systems and assess their potential to host life.

IV. ASTROBIOLOGICAL SIGNIFICANCE

The stellar properties are often considered as the fundamentals for the field of astrobiology, as they influence the potential for life to form and flourish on planets. As we already discussed that in earlier paragraphs, now let's concentrate on planetary factors. The key planetary factors like mass, magnetic field, geological activity, & water availability play crucial roles in determining whether life can begin and persist.

A planet's mass is the most fundamental factor affecting a planet's ability to hold onto an atmosphere, retain internal heat, and maintain geological processes. Smaller planets, like Mars, often lose their atmospheres over overtime due to weak gravity, and massive planets trap thick hydrogen atmospheres, which can prevent the development of Earth-like surface conditions [15]. A mass range roughly between

0.5 & 5 times that of Earth might be optimal for supporting liquid water, geological activity, and a supportive atmosphere [15].

Magnetic field, which is generated through internal dynamics and rotation, is also an important factor. A magnetic field protects the atmosphere from the star's high-energy particles and solar winds. This protection is definitely a critical factor for active stars like M dwarfs, which emit frequent flares that can strip atmospheres [16]. Without a magnetic field, planets lose gases and become inhabitable.

The next one is plate tectonics. They regulate climate and recycle nutrients through the carbonate-silicate cycle. Tectonic activity helps stabilize a planet's surface temperature by controlling atmospheric carbon dioxide levels. Without tectonics, carbon can either be trapped in rocks, causing global cooling, or build up in the atmosphere, leading to runaway greenhouse conditions [17].

Water is definitely essential for life. It might be an Earth-centric thought, but let's keep it aside. The retention and cycling of water through ice, oceans, and vapor might enable the chemical reactions necessary for biology. If planets in the HZ contain water, they might lose it without proper atmospheric protection. Even with an atmosphere, if a planet contains more water than the limit, then land-based ecosystems are not possible [18].

Finally, the planet's age and internal heat supply impact how long life-supporting conditions last. Very young planets may face frequent impacts, and old planets that are geologically inactive may lack the energy to support biological processes.

These planetary factors interact in complex ways that might enhance or reduce a planet's habitability over time. With this understanding of planetary habitability in place, we can now explore classical frameworks used to estimate the prevalence of life in the universe. The next section discusses the Drake Equation, its components, and the challenges in applying it to real exoplanetary systems.

V. LIMITS OF DRAKE EQUATION AND BAYESIAN MODELS

The Drake equation is formulated by Sir Frank Drake in 1961 and is expressed as

$$N = R_* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L \quad \textbf{(1)}$$

Where, R_* is the average rate of star formation per year. f_p is the fraction of those with planetary systems. n_e is the average number of planets per star capable of supporting life. f_l is the fraction of those planets where life actually arises. f_i is the fraction of life bearing planets where intelligent life evolves. f_c is the fraction of intelligent civilizations that develop detectable technology. L is the average length of time such civilizations release detectable signals. N is the number of active, communicative extraterrestrial civilisations in the Milky Way [19].

This equation brings all the factors influencing extraterrestrial life together, but it has significant limitations. Each parameter is uncertain & the equation assumes independence among factors, ignoring the complex interdependencies. It treats the variables as static values, which limits its predictive capability [20].

To aid these issues, Bayesian modeling has been proposed. Rather than fixed values, Bayesian approaches probability distributions to each parameter and update these estimates as we get new data [19]. These models still heavily rely on assumptions and priors that are often speculative due to lack of direct data on extraterrestrial life. Despite these advances, both the Drake equation and Bayesian methods abstract away many astrophysical and planetary processes affecting habitability. This motivates the development of data-driven probabilistic models integrating stellar & planetary conditions.

VI. BEYOND DRAKE: INTRODUCING THE COSMIC LIFE VIABILITY METRIC

The search for extraterrestrial life has relied on models like the Drake equation to know how many intelligent civilizations might exist in our galaxy. Such equations reduce complex astrobiological processes to a handful of averaged terms, often overlooking the detailed physical and chemical conditions that govern habitability. As we get better at understanding stellar systems, planetary evolution, and biosignatures, we must update our models. To address this, I introduce the Cosmic Life Viability Metric (CLVM). It is a probabilistic framework built not to replace the Drake equation but to expand upon it with a more grounded & quantitative approach. This framework integrates stellar & planetary parameters to estimate potential for life in a given system. Unlike earlier models, CLVM holds temperature stability, stellar age, and other critical factors that influence life's emergence and sustainability.

The Cosmic Life Viability Metric (CLVM) is designed to be a one-stop tool that combines astrophysical and astrobiological parameters to assess the likelihood of life in exoplanetary systems. Its construction reflects an interdisciplinary approach, where each contributing function, ranging from stellar classification and planetary mass to magnetic shielding and biosignature potential, is quantified on a continuous scale between 0 and 1. This normalization ensures that the final output, the life viability score, remains bounded within the same range, making cross-system comparisons intuitive and consistent. The formulation is deliberately modular, allowing future empirical findings to refine or replace individual terms without restructuring the entire model. One of the most distinctive aspects of CLVM is the inclusion of a term denoted as Ψ, representing unknown or poorly understood influences that affect life formation. Unlike other parameters based on observable or simulated data, Ψ is designed to capture the uncertainty in current astrobiological knowledge, such as the emergence of self-replicating chemistry or unknown catalytic processes. Its presence acknowledges both the philosophical humility and scientific openness needed when modeling complex phenomena like life.

By leaving room for this unknown factor, the model remains adaptable, inviting future refinements as our understanding deepens through missions, observations, and laboratory work. In this way, the CLVM is not only a present-day analytical tool but also a framework that can evolve with the frontier of life- detection science. Here is the CLVM:

$$P_{\text{life}} = \min(\max(0, \Theta + \Psi), 1) \quad \textbf{(2)}$$

Where, $\Theta = S \cdot f_{hab} \cdot f_{temp} \cdot f_{atm} \cdot f_{age} \cdot f_{bio}$, and $\Psi = \Psi_O + \theta$

So, we can write **equation (2)** as

$$P_{life} = \min(\max(0, S \cdot f_{hab} \cdot f_{temp} \cdot f_{atm} \cdot f_{age} \cdot f_{bio} + \Psi_O + \theta), 1) \quad \textbf{(3)}$$

Let's understand every factor. S is the spectral type weight, a factor representing the general favorability of the star's spectral class for life-bearing output. The values are assigned based on radiation output, life span, and stability. f_{hab} is the habitability zone function; it varies from star to star, and the values are assessed based on the planet's position in the habitable zone. If the planet is far away from the habitable zone, then the value is 0. f_{temp} is the temperature suitability function, a Gaussian function centered around 288K that models how much the surface temperature of a planet is favorable to life. f_{atm} is the atmospheric viability factor, a value between 0 and 1 that estimates how favorable the planet's atmosphere is for supporting life. f_{age} is the stellar age suitability function, a Gaussian function that measures how favorable the age of the host star is for life to emerge and evolve. f_{bio} is the bioavailability factor that brings multiple bio supportive features into a single probabilistic weight. Let's dive further to understand how to assign the values based on observations.
For S, the spectral weight varies with types. As we discussed earlier, G-type is the most promising next, and K-

and M-type follow. So, if the observed star is a G-type, then S=1; if the star is a K-type, then S=0.8; and if the star is an M-type, then S=0.6. Now let's move further onto the next functions.
fhab is the habitability zone function and varies according to the planet's position in habitable zone. To calculate this factor, we must know the following:

$$a_{in} = \sqrt{\frac{L}{1\cdot 1}} \qquad a_{out} = \sqrt{\frac{L}{0\cdot 53}} \qquad \textbf{(4)} \quad \textbf{(5)}$$

Here, a_{in} = Inner edge of HZ, a_{out} = Outer edge of HZ, and L = Luminosity of the star.

$$f_{hab} = \exp\left(-\frac{(a_p - a_{mid})^2}{2\sigma_a^2}\right) \qquad \textbf{(6)}$$

The habitability zone function is a bell curve centered within the habitability zone. This makes the habitability zone function peak at the center of the habitable zone and fall off smoothly towards the edges of habitable zone. Here, a_p is the orbital distance of the planet from the star in astronomical units. a_{mid} is the midpoint of the habitable zone. To find the midpoint of the HZ, add **equations (4) & (5)** and divide it by 2. And σ_a defines the spread or tolerance of HZ. Therefore,

$$a_{mid} = \frac{a_{in} + a_{out}}{2} \qquad \sigma_a^2 = \frac{(a_{out} - a_{in})^2}{4} \qquad \textbf{(7)} \quad \textbf{(8)}$$

Distance (AU)	***fhab*** **(Gaussian)**
0.500	0.00000
0.579	0.00000
0.658	0.00001
0.737	0.00026
0.816	0.00420
0.895	0.03808
0.974	0.19631
1.053	0.57481
1.132	0.95593
1.211	0.90293
1.289	0.48996
1.368	0.15037
1.447	0.02621
1.526	0.00259
1.605	0.00015
1.763	0.00000
1.842	0.00000
2.000	0.00000

TABLE.2 The approximated habitability values based on random orbital distance using the Gaussian formula.

Note: The values in the above table are not based on any exoplanetary data. The aim is to show how the habitability factor changes along with the orbital distance in a star. These values are intended to serve as near-realistic approximations. The Gaussian method can be used for realistic values in G, K, and M-type stars just by adjusting the luminosities and habitable zone ranges.

ftemp is the temperature suitability function, which is assessed based on the surface temperature of the planet. As we know, most of the biochemical processes required for life work the best in the temperature around 288K (Earth-like temperatures) [21]. It is also calculated through Gaussian distribution. Therefore,

$$f_{temp} = \exp\left(-\frac{(T_p - 288)^2}{2\sigma_T^2}\right) \quad \textbf{(9)}$$

Where, T_p is the surface temperature of the planet in Kelvin, and σ_T is the width of the distribution (standard deviation), and values ~20K.

Temperature (K)	***ftemp***
220	0.011
240	0.135
260	0.607
270	0.882
280	0.969
288	1.000
295	0.942
300	0.801
310	0.535
320	0.278
340	0.065
360	0.011

TABLE 3: Temperature suitability based on surface temperature using Gaussian function.

NOTE: The values are obtained using Gaussian probability distribution and are intended to serve as near-realistic approximations. This method can be used for any planet with proper surface temperature analysis.

fatm is the atmospheric factor that represents a planet's atmospheric stability. Atmospheric stability plays a crucial role in maintaining sufficient surface pressure and many chemical processes crucial for life [22]. Since we lack direct atmospheric data, we can assess the values based on estimated indicators.

If the value is near to 1, then the atmosphere might be supportive for life conditions. Here is a table of the assessed values based on the atmospheric types we generally expect to see when we observe a planet.

Atmospheric Condition	**Description**	**Typical *fatm***
Thick H_2/He Envelope	Found in gas giants; not suitable for surface life	0.1 – 0.2
Thin or No Atmosphere	Like Mars or Mercury; unable to retain pressure or block radiation	0.2 – 0.3
Dense CO_2 Atmosphere	Like Venus; leads to extreme greenhouse effect and high surface temperatures	0.3 – 0.5
Earth-like (N_2/O_2-rich)	Supports water cycle, temperature regulation, and biosphere	0.9 – 1.0
Unknown or Unconfirmed Atmospheric Data	No clear spectroscopic data; atmospheric composition unclear	~0.5 (default assumption)

TABLE.4: Tabular description presenting atmospheric conditions and their approximated values.

NOTE: These ranges are estimated based on astrobiological expectations and are intended to serve as near-realistic approximations. So, remember, these values may vary.

f_{age} is the function based on the astrobiological suitability of a star's age for the development and sustainability of life on its planets. Life doesn't appear in seconds or minutes; it requires a mixture of perfect conditions working together for millions of years. If a star is too young (~1 Gyr), then the chances of the star hosting life might be impossible to find due to its frequent impacts and higher stellar activity, and there will be no biosignature stability. If a star is too old (>10 Gyr), then the star might be moving out of its main sequence phase, which might collapse planetary geology, atmosphere, and magnetic field, which are not meant to be habitable. So, a star in the age range (~3-7 Gyr) is considered to be the best because life gets time to develop and sustain itself. On the other hand, the stellar activity will also be stable, leading to better planetary geology and atmosphere. Therefore, we can say that the age of a star definitely matters when we are looking for life outside our solar system. It is calculated through Gaussian distribution. Therefore,

$$f_{age} = \exp\left(-\frac{(T_* - 5)^2}{2\sigma_T^2}\right) \qquad \textbf{(10)}$$

Where, T_* is age of the star in Gyr, $\sigma_T \approx 2$ Gyr (standard deviation; reflects the uncertainty or spread of favourable ages) and the peak values occurs at ~5 Gyr because life will have more likely conditions to arise. Remember, measuring stellar age exactly is very difficult but can be approximated through various methods like Gyrochronology, Cluster dating and many more. If a star's age can't be estimated, then we can put $f_{age} = 0.5$ as a measure of uncertainty.

Stellar Age (Gyr)	**Estimated f_{age}**	**Reasoning**
0.5	0.0439	System too young, causing high instability, frequent impacts, and insufficient time for life to evolve.
1.0	0.1353	Early development is possible, but still not enough time for complex life to form.
2.5	0.7065	Conditions may stabilize, and microbial life could emerge.
5.0	1.00	Peak habitability window; similar to the Sun's age, supports mature biospheres, and can support Earthly conditions
7.0	0.6065	Still potentially habitable, but geological and stellar activity may decline.
9.0	0.1353	Increased risks of resource depletion or environmental degradation.
11.0	0.0439	Reduced energy output and planetary activity are not ideal for life.

TABLE.6: Tabular expression of estimated age function based on stellar age.

NOTE: The values in above table are based on theoretical estimation using a Gaussian function. If we have the stellar age data, we can find age function using **equation (10)**. The reasoning for this function is based but on known principles of planetary science and stellar evolution.

f_{bio} is the bioavailability factor, which is a kind of collective function of multiple factors. It collectively represents the raw materials and internal dynamics required for life to form and flourish. This factor can't be calculated like temperature or age; it can be estimated through the availability of volatile delivery, geological activity, magnetic field strength, core composition, and organic chemistry potential. This is the most difficult part and needs advanced searching techniques, as planetary features can't be estimated directly. If you ask, why are these factors important? Then, volatile delivery is important because, without volatiles like water, carbon compounds, and other building blocks of life, the biochemical potential reduces. Geological activity is important because volcanism and tectonics cycle the nutrients and help a planet to maintain atmospheric composition. Magnetic field strength is important because a stronger magnetic field can protect the atmosphere and planetary surface from harmful radiation, making the place safe and secure for life. Core composition is important because a differentiated interior supports internal dynamics and potentially plate tectonics. Organic chemistry potential is important because the presence of prebiotic chemistry precursors (HCN, CH_4, NH_3, etc.) from atmospheric or hydrothermal processes sets the foundation for more complex biochemical evolution [22],[23].

Condition	Estimated *fbio*	Reason
No volatiles, no geology	0.0 – 0.2	Sterile and no support for basic chemistry
Volatiles but no geology	0.3 – 0.5	Ingredients are present, but weak sustaining processes make it unworthy
Some volatiles and mild geology	0.5 – 0.7	Possible microbial or subsurface life
Active geology with water	0.8 – 0.9	Strong conditions for life development
Earth-like (with magnetic field)	0.95 – 1.0	Ideal environment for complex life

TABLE.7: Tabular representation of estimated values of bioavailability factor based on multiple factors.

NOTE: Minor corrections are to be done as real planetary composition and internal data become available; until then, the above table serves as a near-realistic approximation and is based on astrobiological reasoning.

THE FINAL INFLUENCE: INTERPRETING Ψ

In the Cosmic Life Viability Metric (CLVM) framework, Ψ can be introduced as the final and most uncertain modifier, capturing the influence of factors that remain beyond today's scientific modeling. It is defined as,

$$\Psi = \begin{cases} \Psi_0 + \theta, & \text{if any one function} > 0 \\ 0, & \text{if any one function} = 0 \end{cases} \quad \textbf{(11)}$$

Here, Ψ_0 is the baseline favorability term, representing unknown but non-zero conditions in systems that contain life supporting functions. θ is a dynamic correction term meant to account for unknown influences such as rare geochemical events or unusual molecular pathways. It varies within a conservative range of $-0.05 \leq \theta \leq 0.05$, ensuring it adds nuance without overpowering the structured factors. The value of Ψ_0 is also not derived from direct observations; it is estimated with known life supporting systems and astrobiological reasoning. Assumptions for Ψ_0 reasonably range from 0.2 to 0.25, accounting for less understood parts of today's science. The range from 0.2 to 0.25 might have raised some doubts, so here is my explanation: Ψ_0 is such a term that is unknown to us, but still it has the capability to affect the equation completely. It is like the air we can't see but can feel. So that's why it is associated with such sensitive values so that, if there is life, it supports the equation, and if there is no life, then it turns back to be zero, as every function in CLVM is considered important for lively conditions, and if any one of them is missing, then Ψ turns to be zero. Here is a table for assigning values for Ψ_0 with proper justifications:

System Context	Known Characteristics	Estimated Ψ_0 Range	Rationale
Earth–Sun Analogues	Life-hosting, long-term atmospheric and geological stability	0.2 – 0.25	Strong precedent; real-life example of life emergence under stable conditions
Habitable but Unconfirmed Planets	In habitable zone, good temperature and atmosphere, no biosignatures yet	0.1 – 0.2	Favourable conditions exist, but life is still undetected
Marginal Systems	One or more parameters close to lower bound (e.g., high radiation)	0.05 – 0.1	Some potential, but limited by critical instability or lack of equilibrium
Highly Unfavourable Systems	Star or planet shows active sterilizing behaviour (e.g., flares, toxic gas)	0.0 – 0.05	Extremely low probability; only theoretical allowance for unknown processes

TABLE.8 Guideline table for assigning unknown favourability estimate.

NOTE: This structure ensures that Ψ retains scientific credibility while acknowledging the limits of our current models. It bridges the gap between high-confidence factors and what remains to be discovered, ensuring that, CLVM stays adaptable as new data and theories emerge.

Testing CLVM with Planetary Observables

For the first analysis, let's use Sun-Earth system as an example using the data from NASA's fact sheets [24]. Since Earth is habitable and we exist the probability should be ~1. Let's calculate the functions and test them using CLVM.

Firstly, spectral type weight (S) for a G-type star is 1, from **equation (6)**

$$f_{hab} = \exp\left(-\frac{(a_p - a_{mid})^2}{2\sigma_a^2}\right)$$

$$= \exp\left(-\frac{(1.00-1.164)^2}{2(0.2105)^2}\right)$$

$$= \exp\left(-\frac{0.02689}{0.0886}\right)$$

$$= \exp(-0.3034)$$

Therefore, $f_{hab} \approx 0.74$. It is not ~1 because Earth is not exactly at the center of HZ and gives am realistic estimate. From **equation (9)**,

$$f_{temp} = \exp\left(-\frac{(T_p - 288)^2}{2\sigma_T^2}\right)$$ Since, surface temperature of Earth is ~288K,

$$= \exp\left(-\frac{(288-288)^2}{2\sigma_T^2}\right)$$

$$= \exp(0)$$

Therefore, $f_{temp} = 1$. From **table.4**, $f_{atm} = 0.9$. From **equation (10)**,

$$f_{age} = \exp\left(-\frac{(T_* - 5)^2}{2\sigma_T^2}\right)$$ Since, $\boldsymbol{T_*}$ = 4.6 Gyr (age of Sun) and $\boldsymbol{\sigma_T}$ = 2 Gyr,

$$= \exp\left(-\frac{(4.6-5)^2}{2.2^2}\right)$$

$$= \exp\left(-\frac{(-0.4)^2}{8}\right)$$

$$= \exp\left(-\frac{0.16}{8}\right)$$

$$= \exp(-0.02)$$

Therefore, $f_{age} \approx 0.980$. This shows the Sun is at a very habitable stage in its life. From **table.7**, $f_{bio} \approx 1$. Again, from **table.8** Ψ_O be equal to 0.2 which represents currently unknown life supporting phenomenon, and since, θ represents a small nudge in habitability probability to acknowledge the factors that are supportive but difficult to quantify, let us assume there are some positive affects by the θ factor and let θ = +0.05. Then, Ψ = 0.25. Let's put these results into **equation (3):**

$$P_{life} = \min(\max(0, S \cdot f_{hab} \cdot f_{temp} \cdot f_{atm} \cdot f_{age} \cdot f_{bio} + \Psi_O + \theta), 1)$$

$$= \min(\max(0, 1 \cdot 0.74 \cdot 1 \cdot 0.9 \cdot 0.98 \cdot 1 + 0.20 + 0.05), 1)$$

$$= \min(\max(0, 0.7252 + 0.20 + 0.05), 1)$$

$$= \min(0.9752, 1)$$

Therefore, CLVM predicts that there is a very high likelihood that the taken system can support life, possibly around 97.5% which aligns with what we observe on Earth. And here we can tweak the output by saying, Ψ_O = 0.2248 the, the output will be exactly 'one' showing that life exists in a perfect place. However, the precise cause behind the value 0.2248 is unclear. So, we just used, 0.2 as if we don't know there is life on Earth, but contains some effects supporting life and still unknown. Well, for further analysis and a strong base we have checked the likelihood of a potential system (K2-18).

TESTING CLVM FOR K2-18 SYSTEM

K2-18b is a widely known exoplanet and often considered as highly potential candidate with surface temperature around 265K. It orbits around a M-type star K2-18 which is ~3 billion years old with luminosity 0.0234 times that of our Sun, and ~3 Gyr old. K2-18b is expected to be a Super-Earth planet with hydron rich atmosphere and hints of biosignatures like Methane, DMS and DMDS and water vapor[25]. The values taken for calculations are taken from real data [26]. Let's test CLVM for K2-18b. Firstly, let's see it's spectral weight(S), since it is a M-type star, therefore, S=0.6. Let's move further, from **equation (6):**

$$f_{hab} = \exp\left(-\frac{(a_p - a_{mid})^2}{2\sigma_a^2}\right)$$

$$= \exp\left(-\frac{(0.1429-0.178)^2}{2\ (0.022)^2}\right)$$

$\approx$ 0.63 Therefore, habitability function is $\approx$ 0.63. From **equation (9):**

$$f_{temp} = \exp\left(-\frac{(T_p - 288)^2}{2\sigma_T^2}\right)$$

$$= \exp\left(-\frac{(265-288)^2}{800}\right)$$

$\approx$ 0.52 Therefore, temperature function is $\approx$ 0.52. From **equation (10):**

$$f_{age} = \exp\left(-\frac{(T_* - 5)^2}{2\sigma_T^2}\right)$$

$$= \exp\left(-\frac{(3-5)^2}{2.(2)^2}\right)$$

$$= \exp\left(-\frac{4}{8}\right)$$

$$= \exp(-0.5)$$

$\approx$ 0.607 Therefore, age function is $\approx$ 0.0607. From **table.4,** $f_{atm} \approx 0.5$ because, though we have the atmospherical data, it seems to be a bit uncertain despite the presence of fewer biosignatures. From **table.7**, $f_{bio} \approx$ **0.7** and from **table.8,** $\Psi_O = 0.2$ and let us assume that they are minimal positive effects by the θ factor and let θ = +0.02. Then, Ψ = 0.22. Let's put these values into **equation (3):**

$$P_{life} = \min(\max(0, S \cdot f_{hab} \cdot f_{temp} \cdot f_{atm} \cdot f_{age} \cdot f_{bio} + \Psi_O + \theta), 1)$$

$$= \min(\max(0, 0.6 \cdot 0.63 \cdot 0.52 \cdot 0.5 \cdot 0.607 \cdot 0.7 + 0.20 + \mathbf{0.02}), 1)$$

$$= \min(\max(0, 0.04175 + 0.20 + \mathbf{0.02}), 1)$$

$$= \min(0.26175, 1)$$

Therefore, CLVM (K2-18b) suggests that there is an estimated ~26.2% likelihood that K2-18b might support life. Since, it is a very low estimation, there might be microbial life forming on the planet, but current model can't confirm it up to 100%. As the research advances, the estimates may change and we can get a clear idea about what's going on K2-18b. The calculations are done directly because I already mentioned the respective formulae in earlier sections of the paper.

VII. LIMITATIONS OF CLVM

In this paragraph we are going to discuss the limitations of the Cosmic Life Viability Metric as, discussing the limitations is important for future research modifications. We should first know that, CLVM acts as a probability estimating tool for habitability, and that estimation helps us to figure whether there might be life or not. The estimations might be greater or lower than the original observations. Though it has errors it helps us in in understanding the nature of the observed system. The terms Ψ_O representing the unknown factors effecting life is not calculated based direct observations. It is calculated through theoretical reasoning and analysis with known life bearing systems like Earth, which means its influence, while intentionally bounded, introduces an element of subjectivity into the model. θ should also be considered as an issue to be solved as I lack the exact reasoning for its range and existence but, I believe that there are unnoticed phenomenon that has tiny but crucial effects on formation of life. f_{atm} is often approximated due to lack of data sets available on exoplanetary atmospheres where, real world habitability depends on atmospheric pressure and the presence of greenhouse gases. Many of which are unmeasured for most known planets. f_{atm} and f_{age} are measured using Gaussian function, are centered around Earthly values. Which is an Earth-centric thought and also makes a bit difficult to estimate non-Earthly conditions supporting life like in the case of Titan which is a moon of Saturn.

Another important limitation is dependency incomplete or uncertain data. Many of the key factors like bioavailability factor, stellar age are hard to observe and are modeled, which can introduce minor errors. Moreover, this model becomes unstable while using for high-energy stellar flares or the radiation environment especially, around M-type stars because, they completely effect the planetary conditions, the things on which CLVM is built on.

Due to the small number of confirmed habitable exoplanets, it lacks statistical validation. As such, it should be viewed as a tool rather than a definitive predictor of life. An extension of this model, the enhanced CLVM (eCLVM), was proposed to estimate habitability across groups of similar stars. However, due to a lack of complete and verified data across such groups, eCLVM could not be implemented or tested, and has been removed from the present study. As the future research advancements take place along with the increase in exoplanetary data from JWST and Kepler and TESS missions, CLVM can be validated and with some changes, it can be used as a potential life predictor with minor adjustments that I couldn't figure out. I've given my conclusions in the following paragraph.

VIII. CONCLUSION

We began with a review of stellar classification and stated that G, K, and M-type stars as key candidates for hosting life, based on their stability and abundance. We explored the (M-R-L) relations in a simple way and saw the importance of stellar metallicity in the formation of planets and habitability zone dynamic. We talked about how planets and their environments can support life through astrobiological significance. Then, we understood the limitations of the Drake Equation and Bayesian models, and introduced the Cosmic Life Viability Metric (CLVM), a probabilistic tool designed to estimate the likelihood of life in star-planet systems using the important parameters.

CLVM was then, applied to both the Earth–Sun system and the exoplanet K2-18b, demonstrating a perfect matching with known biological potential when real data and Gaussian modeling were used. Nevertheless, due to the limited availability of confirmed data on habitable exoplanets, many of the values in CLVM were calibrated using Earth as a reference. This Earth-centric approach was necessary to ensure grounding in a known life-hosting environment, while still allowing adaptability across diverse systems.

A key strength of the CLVM is its incorporation of the Ψ_0 term, a baseline favourability component that is sensitive to the completeness of a planet's life-supporting conditions. Since not every star hosts planets, not every planet lies within the habitable zone, and not every habitable-zone planet guarantees life, the design ensures that if any one of the primary CLVM factors is absent or unsuitable, Ψ_0 effects the life potential by dropping to zero. This ongoing interaction keeps the model in line with both hopeful and cautious views about life in space.

In summary, CLVM presents a flexible and scientifically grounded alternative to traditional life-estimation methods. While still theoretical, it offers a solid framework for future refinement as observational capabilities improve, helping to prioritize targets in the ongoing search for life beyond Earth. So, what do you think? Do we have cosmic neighbours?

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