

The Venus Life Equation

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Abstract

Ancient Venus and Earth may have been similar in crucial ways for the development of life, such as liquid water oceans, land-ocean interfaces, the favorable chemical ingredients and energy pathways. If life ever developed on, or was transported to, early Venus from elsewhere, it might have thrived, expanded and survived the changes that have led an inhospitable surface on Venus today. Today the Venus cloud layer may provide a refugium for extant life. We introduce the Venus Life equation - a theory- and evidence-based approach to calculate the probability of extant life on Venus, L , using three primary factors of life: Origination, Robustness, and Continuity. We evaluate each of these factors using our current understanding of Earth and Venus environmental conditions from the Archean to the present. We find that probability of origination of life on Venus is similar to that of the Earth and argue that the other factors are nonzero, yielding a probability of extant life of Venus of ≤ 0.1 . The Venus Life Equation identifies poorly understood factors that can be addressed by direct observations with future exploration missions.

Introduction: One of the biggest motivators for exploring the solar system beyond Earth is examining whether extant life currently exists, or now-extinct life once existed, on worlds beyond ours. Our current state of knowledge of the past and present climate of Venus suggests it once had an extended period – perhaps 2 billion years – where a water ocean – and a land-ocean interface could have existed on the surface, in conditions resembling those of Archaean Earth (Way *et al.*, 2016; Way and Del Genio, 2020). Although today Venus’ surface (450°C, 90 bars) is not hospitable to life as we know it, there is a zone of the Venus middle atmosphere, at around 55 km altitude, just above the sulfuric acid cloud layer, where the conditions are reasonably Earth-like (Figure 1) (Cavicchioli, 2002). The question of whether life could have – or could still – exist on the Earth’s closest neighbor is in fact more open today than it’s ever been (Morowitz and Sagan, 1967; Limaye *et al.*, 2018; Seager *et al.*, 2020). This paper approaches the question of extant life on Venus in a similar manner as Drake Equation (Burchell, 2006). We approach the question of whether life exists currently “on” Venus (we include the planet’s atmosphere in this definition) as an exercise in informal probability – seeking qualitatively the likelihood or chance of the answer being nonzero.

The Venus Life Equation: The Venus Life Equation (Figure 2) is expressed as:

$$L = O \cdot R \cdot C \quad (1)$$

where L is the likelihood (zero to 1) of there being life currently in a sustained airborne Venus ecosystem, O (origination) is the chance life ever began on Venus and survived long-term, R (robustness) is the potential current and historical size and diversity of the Venus biosphere, and C (continuity) is the chance that conditions amenable to life persisted spatially and temporally to the present. The following sections describe each variable.

Origination: Life on a planet can start via independent abiogenesis, or importation from elsewhere (panspermia), where:

$$O = O_A + O_P, \quad (2)$$

or possibly:

$$O = 1 - ((1 - O_A) \cdot (1 - O_P)) \quad (3)$$

where O_A is the likelihood of origin by *abiogenesis* and O_P is the likelihood of origin by *panspermia*. The difference between Eqns. 2 and 3 is that Eqn. 3 removes a potential double-counting if life has arisen by both abiogenesis and panspermia, i.e., the probability of two separate geneses. If O_A and O_P are both small, this difference is negligible.

O_A depends on how likely it is for life to independently arise. In our own solar system, empirically, we assign $O_A \sim 1$ for Earth. For other bodies, for lack of other definitive evidence, we assume the baseline is effectively zero, with probabilities increasing as current or historical conditions become similar those of early Earth. O_P in our solar system may be nonzero from possible transportation of life due to impacts emanating from Earth, at the very least (Nicholson, 2009; Beech *et al.*, 2018). Because of its relative proximity and size, Venus is the most likely to receive viable life from Earth (Gladman *et al.*, 1996), and thus, over geologic history, we can estimate a value of $O_P \sim 0.1-0.5$. But just starting life would not be enough to result in a sustained biosphere.

For the purposes of life that we might be able to detect with astrobiological investigations, *breakout* is an essential component of origination. It is the chance life escaped its point of origin to spread across the planet. On Earth life may have arisen, once, or dozens or thousands of times in different surface or subsurface regions only to be snuffed out by events for which we have no

record. This is encapsulated in the variable O_b , which for Earth became 1 early in its history. If we assume early Venus was similar to Archean Earth for 2+ billion years, an O_b of 0.9 to 1 for Venus may be reasonable.

Accounting for breakout modifies the Origination term:

$$O = (O_A + O_P) \cdot O_B \quad (4)$$

or:

$$O = (1 - ((1 - O_A) \cdot (1 - O_P))) \cdot O_B \quad (5)$$

On Venus, example estimates for the subfactors might range from 0.1 (or below) as “low” and 0.4 as “high” as a starting probability span for life getting a foothold on the second planet.

Planetary and Astrobiology Study of Origination: Origination of life is a fundamental current focus of evolutionary biology and astrobiology alike. Understanding the possibility of independent origination of life on Venus benefits substantially from investigations of life’s origins on Earth, and on understanding how similar and how different conditions on early-Venus were from Archean and Hadean Earth. Assessing the likelihood of transfer from Earth or other life abodes to Venus would benefit from statistical modeling of the survivability of life as we know between the solar system’s rocky planets (e.g., Nicholson *et al.*, 2009). Favorable biochemical conditions on several Ocean worlds in the outer solar system may have allowed life to arise. But outer worlds will have a lower chance of exchanging materials with rocky planets like Earth and Venus. Observation and modeling of the frequency of atmospheric impacts within solar systems (e.g. Harrington *et al.*, 2004) and the aerobraking effects on materials delivered will also help constrain Origination factor estimates for atmosphere-rich giant planets and exoplanets.

Further exploration of our own system’s potential abodes, and examination of the properties and statistics of the growing number of known planets outside the solar system (Seager

et al., 2016; Rossmo 2017); may allow the Venus Life Equation to help estimate the probability of life on exoplanets, and vice versa.

Why O is not zero for Venus: Current models suggest that early Venus conditions paralleled those of early Earth during the period in which Earth life arose (Way *et al.*, 2016; Way and Del Genio, 2020), which, absent other information supports an Earth-like value of $O_A \sim 0.9 \sim 1$. Regardless of a potential independent biogenesis on Venus, we know that lithopanspermia subfactors outlined in O_p would have sent endolithic terrestrial microbes towards the planet throughout its habitable history, yielding an estimate of $O_p \sim 0.1-0.5$.

Robustness: Life on Earth has survived in part because it spread so widely, with such variety and quantity; it was therefore hard to completely eradicate during acute or gradual environmental changes. An estimation of this robustness may be expressed with:

$$R = R_b \cdot R_d \quad (6)$$

where R_b is a measure of potential *biomass* supported over time, and R_d is a similar measure of potential *diversity*.

On Earth, the value of R has been sufficiently high to allow survival through dramatic climate events, near-global mass extinctions, and other regional changes delivering stress or pressure on ecosystems. R can be considered to represent the “best case” for a planetary biosphere at a given time, which is then multiplied by other terms representing losses or threats to produce a probability of continued survival. If enough data are available for a given planet to define different epochs, then historical subvalues of R can be weighted by risks specific to each epoch to yield a more precise estimate of overall R.

Planetary and Astrobiology Study of Robustness: Like O, R is affected by the “n=1” problem. Earth, past and present, is our only example of a biosphere. It is possible for us to estimate how much lower an Earth-like planet’s R could be under less-favorable global conditions, using results from studies of life in extreme environments, comparative ecology, paleoclimatology, and the like. However, it is much more difficult to make conservative estimates about a planet theoretically more habitable than Earth. To account for these limits, we define R here as a fraction of R_{Earth} , and let $R_{\text{Earth}} = 1$. This makes our bias explicit, and allows a straightforward recalculation if one wishes to make different assumptions about Earth’s relative habitability.

Biomass on Earth, on a planetary scale, is usually quantified as either organically bound carbon (Gt C) or primary production (Gt C · yr⁻¹). Both measures assume biospheres based on carbon; the former assumes that the majority of organic carbon is biogenic; the latter is intended to account for extant life being recycled and dead organic matter accumulating. None of these are necessarily true for other potential biospheres (NRC, 2007). However, part of the astrobiological appeal of Venus is its similarity to Earth during the early period in which life may have arisen, implying a similar potential biochemistry. We know very little about the possible productivity of a modern Venus ecosystem, although some potential nutrient sources have been proposed (Schulze-Makuch *et al.*, 2004, Limaye *et al.*, 2018). We therefore use estimates of Earth's R_b in Gt C as a baseline.

Though much remains unknown about Venus's past history, it is clear that its early state, modeled to have clement oceans, is very different from its current state, in which liquid water cannot exist on the surface and the most commonly suggested extant habitat is aerosols within certain bands of the cloud layers. Early Venus is speculated to be relatively similar to early Earth, so we use early Earth as a reasonable template for estimating R_b for early Venus. Although much

remains unknown about Earth's Archaean biosphere, some estimates place it in the range of 100 - 400 Gt C (Franck *et al.*, 2005), about 0.2 - 0.7 times Earth's current biomass (~550 Gt C) (Bar-On *et al.*, 2018).

On Earth, biomass over time has been sufficient to allow survival despite dramatic climatic change and near-global extinction events. Here, reasoning by analogy for Venus becomes more challenging. The most commonly argued case for life on modern-day Venus is that life originated in the oceans and could have colonized the dense, persistent cloud layer and endured there after the loss of the surface oceans (Grinspoon and Bullock, 2007). However, Earth has no habitat directly analogous to Venus's cloud layer. The closest regime, in terms of chemistry and isolation from surface nutrient and water sources, is probably the stratospheric sulfate layer (Gentry and Dahlgren, 2019), where the longest-enduring microbe-sized aerosols may have residence times of years. However, under stratospheric conditions it is likely impossible for terrestrial microorganisms to metabolize, grow, or reproduce. Survivors recovered at extreme heights above the Earth's surface tend to be dormant, resilient, endospore-forming bacteria enduring harsh irradiation until dropping out by gravitational settling (Bryan *et al.*, 2019). At lower altitudes, terrestrial aerobiologists are exploring whether short-lived airborne ecosystems exist within Earth clouds where environmental conditions are more favorable, including water and nutrient availability (Amato *et al.*, 2019). Additional in-situ cloud microbiology measurements will be required before it can be determined if some life on Earth is periodically "independent" of the planet's surface (Smith, 2013) (Figure 3).

If a terrestrial analogue environment existed, we could estimate R_b as the typical biomass supported in the analogue environment, multiplied by the size of the target environment. For example, if the biomass supported in Earth's sulfate aerosol layer were m Gt C per m^3 with a

particle density of n per m^3 , the potential R_b for Venus could be estimated as m/n , multiplied by the particle density and volume of Venus's haze layer.

As an example of how to apply the Robustness subfactors, we can place an order-of-magnitude upper bound on the R_b estimate using a similar approach. Let's assume that *all* the particles in Venus's cloud layer larger than $0.2 \mu m$, the lower end of terrestrial microbes' size range, are putative microorganisms. A quick calculation using reported particle concentrations (Esposito *et al.*, 1984) yields a count of 5×10^{24} potential organisms. By comparison, the estimated number of prokaryotes on Earth is in the range of 4×10^{30} (Whitman *et al.*, 1998). These assumptions yield an upper limit on the current R_b of Venus of ~ 0.000001 . Other suggestions that have been put forward for Venus include surface life adapted to use supercritical carbon dioxide as a solvent (Budisa and Schulze-Makuch, 2014), and subsurface microbes in refugia of highly pressurized water (Schulze-Makuch *et al.*, 2005). R_b can be recalculated considering these farther-ranging hypotheticals to produce a different answer (this is left as an exercise for the reader).

Life on Earth, which represents our baseline $R_b \sim 1$, is incredibly diverse, where nearly every liquid and solid surface measured to date is colonized with a well-developed ecosystem. Even more so than with biomass, there are a wide variety of biodiversity metrics in use, and each reflects one or more terrestrial biases. As is perhaps to be expected, more quantitative metrics, such as taxonomic diversity, are also less extensible to other theoretical biospheres. Functional diversity, which reflects how many distinct niches life can occupy in a given habitat -- e.g., "apex predator (obligate heterotroph)" or "primary producer (sulfur-reducing chemolithotroph)" -- is probably the most intuitively applicable to a theoretical non-terrestrial biosphere. As with biomass, the metric chosen should reflect constrainable similarities between Earth and Venus.

We know very little about the biodiversity of Archaean Earth, even as an analogue. For hundreds of millions of years, early Earth lacked several major functional niches present today (Nisbet, 1995), including oxygenic photosynthesis and all, or nearly all, land-based ecology. We have no way of knowing how many historical niches may once have existed -- e.g., chemolithotrophs utilizing minerals only stable in a reducing atmosphere -- but are now lost. We know even less, of course, about early Venus. However, since R is meant to represent a best-case, and we know that any extant life on Venus is almost certainly a relic of a more thriving era, we can pick an example range for early Earth's R , of 0.1 - 0.5 and use this as our estimate for early Venus as well.

Modern-day Venus is a more tractable case. Although, as with R , there is no direct analogue, we can at least estimate an upper bound based on partial analogue reasoning. Chemically speaking, terrestrial acid hot springs have been proposed as the inhabited environments that most closely reproduce Venus cloud temperature (97 – -45°C) and pH (less than -1.3 to 0.35) (Grinspoon and Bullock, 2007; Krasnopolsky, 2019), whereas deserts or concentrated brines may best represent the low water activity in Venus aerosols (~0.02 at a relatively optimistic assumption of 75% H_2SO_4 and 25% H_2O) (Deno and Taft, 1954; Hansen and Hovenier, 1974; Kleft, 2003; Bolhuis *et al.*, 2006). Each of these environments show significantly less diversity than more typical mesophilic environments. At pH levels at or below 1, terrestrial life is limited to a few lineages of archaea (Barrie Johnson and Hallberg, 2008). Brines at water activities below 0.75 are similarly limited to other lineages of archaea (Grant, 2004; Oren, 2011). Life forms in both environments are restricted in the metabolic pathways which occur (Barrie Johnson and Hallberg, 2008; Oren, 2011) - although (complicating the analogy) the modern archaeal isolates are generally aerobic heterotrophs, a strategy which appears to have emerged via horizontal gene transfer with bacteria

(Fütterer *et al.*, 2004; Sorokin *et al.*, 2017). Only the most extreme deserts on Earth approach water activities below 0.1, and here, though more taxonomically diverse, life is primarily phototrophic, adapted to long periods of inactive desiccation followed by brief bursts of activity during sporadic water influx.

Why R Is Not Zero for Venus: Because R represents a “best-case” biosphere, it could only be zero for a target environment which meets no known criteria for habitability -- for example, the sun, dry lunar regolith, or the exposed surface of an asteroid. While the potentially supportable biosphere on modern Venus may be quite low or limited by terrestrial standards, the relative clemency of early Venus, and its similarity to the empirically inhabited early Earth, means R should not be zero.

Continuity: This factor reflects the necessity of continuous existence of habitats over time and space; or, equivalently, the lack of global extinction-level events. Environmental continuity is affected by both internal and external factors. The former includes variations in the carbonate/water cycles that are governed by plate recycling, rates of volcanism and rock weathering. Study of the composition and deformation histories of the most ancient terrains on Venus (tesserae) may help determine the presence, extent and duration of some of these factors (e.g. Gilmore *et al.*, 2017). External factors include solar-system wide events such as stellar variability (life-threatening flares/CMEs), stellar aging (changing luminosity inducing climatic shifts), and large impactors. (Bostrom and Circovic, 2011; Chapman and Morrison, 2013). Some of these external factors, such as stellar lifetime, are empirically known to be 1 for Venus by the continuing presence of life on neighboring Earth. Others, such as activity sufficient to sterilize life

only out to 0.8 AU, or an extinction-level coronal mass ejection while Venus and Earth were in opposition, must be estimated.

Continuity can be quantifiably constrained for Venus through direct measurement; determining the availability of current resources in potential niches (e.g. the elements C, H, N, O, P, & S and solvents as necessary building blocks for Earth-like biology in Venus clouds), and through unraveling the geologic history of the planet to determine if a continuous path might have been available for life to evolve to survive and maintain itself for tens or hundreds of millions of years of post-ocean Venus history. For example, one possible pathway to extant Venus life would require conditions to evolve contiguously and continuously from a marine-land interface (e.g. one of the likely ‘breakout’ environments for Earth), to a globe-spanning biosphere, to eventual adaptation towards complete airborne life cycles and a biosphere maintainable solely in the clouds.

Complications for continuity are rooted in both understanding of terrestrial biology and lack of understanding of Venus’ geologic history and present conditions. If one assumes a “terrestrial-like” biochemistry, neither the trace composition of Venus’s aerosols nor current conditions such as atmospheric circulation of dust are understood well enough to determine water activity or the presence of bioavailable forms of nitrogen and phosphorus, let alone the more rare ‘essential’ heavy elements like Fe, Zn, Pb, Cu, Sn, V, Cd, Ni, Se, Mn, Co, Cr, As, Mo and W. Detections of both phosphorus and iron were reported by the Vega X-ray fluorescent radiometers (Andreychikov *et al.*, 1987), but a comprehensive trace elemental assay of the Venus clouds, with sensitive 21st century instruments, has not been performed. Also, it must be kept in mind that what is observed to be an “essential” element in the terrestrial biota is also the product of an opportunistic evolutionary process which might well have found “work arounds” in other planetary environments with a different complement of available elements. More exotic proposed

biochemistries (such as direct use of sulfuric acid as an alternative polar solvent) are even less constrained in terms of energy and chemistry requirements (Schulze-Makuch and Irwin, 2008; Cockell and Nixon, 2016).

Non-chemical requirements are also critical. Energy pathways such as photosynthesis or chemosynthesis need to have been established and maintained or evolved to in a similar contiguous and continuous manner. For example, although Venus receives more photonic energy at the top of its atmosphere than Earth, the thick atmosphere and haze layer reflect or block larger fractions of it. This is particularly important for a potential atmospheric ecosystem, as the residence time of potential aerosol habitats imposes a particular constraint. Many terrestrial microbes in extremely harsh or nutrient-limited environments have very long generation times of weeks to months, potentially in combination with long periods of inactivity. If microbe-bearing aerosols, on average, settle out (as on Earth) or fall to an altitude at which they dry out or boil off (as on Venus) faster than the microbes can reproduce, an aerosol-based biosphere without periodic injections from other reservoir habitats will not be stable over the long term, even if short-term conditions are otherwise favorable.

One of the major sub-factors of C specific to Venus is the timeline of Venus's water loss and cloud formation. Although life is capable of very rapid adaptation and diversification in some circumstances, major habitat transitions on Earth such as colonization of land took at least hundreds of millions of years. The shorter the period of overlap between the potential origination of life in the oceans and the formation of the modern-day habitat of persistent cloud cover, the lower the likelihood of colonization; and if the two did not overlap at all, it would be negligible at best. Though this timeline is not currently well constrained, there may have been a gap between

the end of Venus' surface oceans and the current thick cloud deck of 10s Myr to 100s Myr (Way and Del Genio, 2020).

Planetary and Astrobiology Study of Continuity: Continuity is hard to estimate given how little we know about both Venus' history and current potential habitats. However, of the three factors of the Venus Life Equation, it is the one we can do the most to improve quantification through direct study of Venus and its history. Most of the areas delineated in the Goals, Objectives, and Investigations for Venus Exploration (VEXAG, 2019) document will result in direct quantitative improvement of the estimate for C. For example, determining the presence and extent of silicic igneous rocks constrains the history of possible early Venus oceans and crustal evolution. Measuring isotopic ratios of noble gases, oxygen, hydrogen in the atmosphere will constrain the history of water, and possibly biological or prebiotic effects on global chemistry. Deep dynamics will constrain the possibility of circulation of materials from near the surface through the lower atmosphere, and geologic history and activity will determine the present and past supply of chemicals to different parts of potential Venus ecosystems. The entirety of Goal 1, in fact, prioritizes the understanding of Venus' early history and potential habitability.

Why C Is Not Zero for Venus. At the moment, this could be the most difficult stipulation of the Venus Life Equation. We simply don't know enough about Venus' evolution to do more than make model and geologically and evolutionary plausible 'what if' scenarios. Assigning for C a range of 0.1 to 0.5 may be generous, or not. Continuity estimates can only be vastly improved with each new mission we send to Venus.

Life: With estimates for all 3 factors for Venus, we can calculate a range for the chance of life. Using example low and high values throughout:

$$L = 0.1 \cdot 0.1 \cdot 0.1 = 0.001 \text{ (low) or} \quad (7)$$

$$L = 0.4 \cdot 0.5 \cdot 0.5 = 0.1 \text{ (high)} \quad (8)$$

These numbers are simply example estimates. Individual investigations and additional constraints, experiments, or observations may drive any one of the factors or subfactors higher, or perhaps more likely, lower. This exercise can be performed for any potential abode of life in our solar system and adapted and estimated for any potential habitable world. For example, the known and theorized sub-ice oceans on several icy moons (and Pluto) harbor several niches and pathways that might increase R or C in the equation, with O_i from the inner solar system being statistically smaller. The atmospheres of the giant planets require a different set of assumptions for sources and renewability of potential heavier elements for life processes. In all these cases, for our own solar system, we know where to look and what we can measure to more quantitatively constrain these factors. It's just a question of going there and doing it with missions. Although a similar exercise may well reveal several environments on solar system bodies having ranges of estimated L which exceed that of Venus, at least on the high end of the range, any strategy for astrobiology exploration must also factor in the accessibility of the potentially habitable environment. Venus is the nearest planet to Earth in both average distance and delta-V. A non-negligible estimate for L on Venus would seem to argue strongly for exploratory missions operating within the cloud environment as part of any comprehensive strategy to look for extant life in the solar system.

Estimates of both R and C are complicated by an observability bias. Though we can speculate about the existence, size, and complexity of a potential habitat by extrapolating from what we know of Earth life, ultimately, the only thing that conclusively proves habitability is inhabitation. This is the primary reason for separating R into a "best case" biosphere and C into the probabilistic challenges to R; it allows the likelihood of a surviving biosphere to be captured

in the traditional sense, as a product of desired outcome and estimated probability. However, if any R term could be directly measured, then L would be one or zero, empirically (or at least for that epoch; the equation could still be used to estimate the likelihood of an extant biosphere given only evidence of past life). The Venus Life Equation is intended to be an exercise in identifying assumptions and needed constraints for a planet for which direct life detection efforts have yet to be attempted.

Beyond Venus: The L determined by the Venus Life Equation, adapted for and integrated over many possible worlds, is related to the term f_i of the Drake Equation (Burchell, 2006): the fraction of planets in our galaxy that develop life. The equation applied to Venus shows how we might approach questions of habitability on worlds beyond Earth.

Consequences for Planetary Protection: Currently, NASA classifies Venus missions under planetary protection Category II, which “includes all types of missions to target those bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration,” (NAS 2006). The National Academies (2006) recommended that the Category II planetary protection classification of Venus be retained. With respect to forward contamination of Venus clouds, this recommendation is based on the conclusion that “the cloud droplets consist of concentrated sulfuric acid, any terrestrial organisms would be rapidly destroyed by chemical degradation.”

The only terrestrial life that might endure conditions in Venus aerosols are extreme acidophiles, which have not been observed to survive long periods of time airborne and are unlikely to be clean-room contaminants. This is true even if one assumes that putative extant Venus microbes rely on substantially different metabolic inputs and outputs from possible

transported terrestrial life to the point that the "potentially habitable region" for each does not overlap. This implies that the types of possible terrestrial (bio)chemical contamination that could survive exposure to Venus atmosphere/aerosols are unlikely to cause false positives in experiments looking for Venus life. The NAS study did not recommend any scientific investigations for the specific purpose of reducing uncertainty with respect to planetary protection issues. Thus, the Category II classification of the NAS study remains unchallenged by a nonzero value for L. Like any life detection experiment, however, any in-situ instrumentation will need to invoke a high level of internal protection to ensure accurate measurement.

Conclusion: The Venus Life Equation allows an estimation of the probability of extant life on Venus can be made by examining the Earth analog, improving our understanding of planetary bodies in our solar system, and studying current conditions on Venus. The chances of life originating and surviving on Venus to today are low, but nonzero. Improved in-situ observation of conditions on Venus, especially in the potentially habitable zone in its middle atmosphere will help to constrain any estimate for Venus and other cloudy worlds. Adaptation and expansion of the Origination, Robustness, and Continuity factors to additional bodies within and outside our solar system will allow adaptation of the equation's principles to other potential biospheres.

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References

- Amato P, Besaury L, Joly M, Penaud B, Deguillaume L, Delort AM. Metatranscriptomic exploration of microbial functioning in clouds. *Scientific Reports* 2019;9(1):4383. doi.org/10.1038/s41598-019-41032-4
- Andreychikov BM, Akhmetshin IK, Korchuganov BN, Mukhin LM, Ogorodnikov BI, Petryanov IV, Skitovich VI. X-ray radiometric analysis of the cloud aerosol of Venus by the Vega 1 and 2 probes. *Cosmic Res* 1987;25:16.
- Bar-On YM, Phillips R, Milo R. The biomass distribution on Earth. *P Natl Acad Sci* 2018;115 (25):6506–11. <https://doi.org/10.1073/pnas.1711842115>.
- Barrie Johnson D, Hallberg KB. Carbon, iron and sulfur metabolism in acidophilic microorganisms. *Adv Microb Physiol* 2008;54:201–55. doi.org/10.1016/S0065-2911(08)00003-9
- Beech M, Coulson IM, Comte M. Lithopanspermia – The terrestrial input during the past 550 million years. *Am J Astron Astroph* 2018;6(3): 81-90.
- Bolhuis H, Palm P, Wende A, Falb M, Rampp M, Rodriguez-Valera F, Pfeiffer F, Oesterhelt D. The genome of the square archaeon *Haloquadratum walsbyi*: Life at the limits of water activity. *BMC Genomics* 2006;7(1),1. doi.org/10.1186/1471-2164-7-169
- Bostrom N, Cirkovic MM, eds. *Global catastrophic risks*. 2011 Oxford University Press.
- Bryan NC, Christner BC, Guzik TG, Granger DJ, Stewart MF. Abundance and survival of microbial aerosols in the troposphere and stratosphere. *ISME Journal* 2018;13,11:2789-2799.
- Budisa N, Schulze-Makuch D. Supercritical carbon dioxide and its potential as a life-sustaining solvent in a planetary environment.” *Life* 2014;4 (3):331–40. doi.org/10.3390/life4030331
- Burchell MJ. W (h)ither the Drake equation? *Int J Astrobio* 2006;5(3):243-250.

- Cavicchioli R. Extremophiles and the search for extraterrestrial life. *Astrobiology* 2002;2,3:281-292.
- Chapman CR, Morrison D, eds. *Cosmic catastrophes*. 2013 Springer.
- Cockell CS, 1999. Life on Venus. *Planet Space Sci* 1999;47(12):1487–1501. doi.org/10.1016/S0032-0633(99)00036-7.
- Deno NC, Taft RW. Concentrated sulfuric acid-water. *J Am Chem Soc* 1954;76(1):244–248. doi.org/10.1021/ja01630a063
- Esposito LW, Knollenberg RG, Marov MYa, Toon OB, Turco RP. The clouds and hazes of Venus. *Venus*, Univ. Ariz. Press, Humten DM, Colin L, Donahue TM, Moroz VI. eds. 1984;16:484-564.
- Franck S, Bounama C, von Bloh W. Causes and timing of future biosphere extinction. *Biogeosci Disc* 2005;2(6): 1665–79. doi.org/10.5194/bgd-2-1665-2005.
- Fütterer O, Angelov A, Liesegang H, Gottschalk G, Schleper C, Schepers B, Dock C, Antranikian G, Liebl W. Genome sequence of *Microphilus torridus* and its implications for life around PH 0. *P Natl Acad Sci* 2004;101(24):9091–96. doi.org/10.1073/pnas.0401356101.
- Gentry D, Dahlgren RP. Venus aerosol sampling considerations for in situ biological analysis. *The Venera-D Landing Sites and Cloud Habitability Workshop* 2019: Moscow, Russia.
- Gilmore MS, Treiman A, Helbert J, Smrekar S, Venus surface composition constrained by observation and experiment. *Space Sci. Rev.*, 2017;11:(1-30). doi:10.1007/s11214-017-0370-8.
- Gladman BJ, Burns JA, Duncan M, Lee P, Levinson HF, The exchange of impact ejecta between terrestrial planets. *Science* 1996;271:1387–1392.
- Grant WD. Life at low water activity. *Phil Trans Royal Soc Bio Sci* 2004;359(1448):1249–67. doi.org/10.1098/rstb.2004.1502.

- Grinspoon DH, Bullock MA. Astrobiology and Venus exploration.” *Geophys Monograph Series* Esposito LW, Stofan ER, Cravens TE eds. 2007;176:191–206. Washington, D. C.: AGU. doi.org/10.1029/176GM12.
- Hansen JE, Hovenier JW. Interpretation of the polarization of Venus. *J Atmo Sci* 1974;31:1137–1160. doi.org/10.1175/1520-0469(1974)031
- Harrington JdPI, Brecht SH, Deming D, Meadows V, Zahnle K, Nicholson PD. Lessons from Shoemaker-Levy 9 about Jupiter and planetary impacts. *Jupiter: The Planet, Satellites and Magnetosphere*. F. Bagenol, T. Dowling, W. McKinnon, eds. Cambridge Univ. Press. 2004;8:158-84.
- Kieft TL. Desert environments: Soil microbial communities in hot deserts. Bitton G ed. *Encyclopedia of Environmental Microbiology* Wiley 2003;1–25. doi.wiley.com/10.1002/0471263397.env178
- Krasnopolsky VA. *Spectroscopy and Photochemistry of Planetary Atmospheres and Ionospheres*. Cambridge University Press 2019;243. doi. 10.1017/9781316535561
- Limaye SS, Mogul R, Smith DJ, Ansari AH, Słowik GP, Vaishampayan P. Venus’ spectral signatures and the potential for life in the clouds. *Astrobiology* 2018;18(9):1181–98. doi.org/10.1089/ast.2017.1783
- Morowitz H, Sagan C. Life in the clouds of Venus. *Nature* 1967;215:1259-1260.
- NAS (National Academies of Sciences Engineering and Medicine). Assessment of Planetary Protection Requirements for Venus Missions: Letter Report (2006). *National Academies Press*, 2006;16p.
- Nicholson WL. Ancient micronauts: interplanetary transport of microbes by cosmic impacts. *Trends Microbio* 2009;17(6):243-350.

Nisbet EG. Archaeal ecology: A review of evidence for the early development of bacterial biomes, and speculations on the development of a global-scale biosphere. *Geological Society, London, Special Publications* 1995;95(1):27–51. doi.org/10.1144/GSL.SP.1995.095.01.03

NRC (National Research Council). The limits of organic life in planetary systems. Washington, D.C.: *National Academies Press* 2007. doi.org/10.17226/11919.

Oren A. Ecology of halophiles. *Extremophiles Handbook* 2011;1:344–61. Springer. doi.org/10.1007/978-4-431-53898-1_3.4

Rossmo DK. Bernoulli, Darwin, and Sagan: the probability of life on other planets. *Intl J Astrobio* 2017; 16(2):185-9.

Schulze-Makuch D, Grinspoon DH, Abbas O, Irwin LN, Bullock MA. A sulfur-based survival strategy for putative phototrophic life in the Venusian atmosphere. *Astrobiology* 2004;4(1): 11–18. doi.org/10.1089/153110704773600203.

Schulze-Makuch D, Dohm JM, Fairén AG, Baker VR, Fink W, Strom RG. Venus, Mars, and the ices on mercury and the moon: Astrobiological implications and proposed mission designs. *Astrobiology* 2005;5(6):778–95. doi.org/10.1089/ast.2005.5.778.

Schulze-Makuch D, Irwin LN. Definition of life. In *Life in the Universe* 2008;7-24. Springer, Berlin, Heidelberg.

Seager S, Bains W, Petkowski JJ. Toward a list of molecules as potential biosignature gases for the search for life on exoplanets and applications to terrestrial biochemistry. *Astrobiology* 2016;16(6):465-85.

Seager S, Petkowski JJ, Gao P, Bains W, Bryan NC, Ranjan S, Greaves J. The Venusian lower atmosphere haze as a depot for desiccated microbial life: a proposed life cycle for persistence of the Venusian aerial biosphere”, *Astrobiology*, 2020; in press

- Smith DJ. Microbes in the upper atmosphere and unique opportunities for astrobiology research. *Astrobiology* 2013;13(10): 981-990.
- Sorokin DY, Messina E, Smedile F, Roman P, Damsté JSS, Ciordia S, Mena MC, *et al.* Discovery of anaerobic Lithoheterotrophic Haloarchaea, ubiquitous in hypersaline habitats. *The ISME Journal* 2017;11(5):1245–60. doi.org/10.1038/ismej.2016.203.
- VEXAG (Venus Exploration Analysis Group). Venus Goals, Objectives, and Investigations 2019 https://www.lpi.usra.edu/vexag/reports/VEXAG_Venus_GOI_Current.pdf
- Way MJ, Del Genio AD, Kiang NY, Sohl LE, Grinspoon DH, Aleinov I, Kelley M, Clune T. Was Venus the first habitable world of our solar system? *Geoph Res Lett* 2016;43(16) 8376-8383.
- Way MJ, Del Genio ADD. Venusian habitable climate scenarios: Modeling Venus through time and applications to slowly rotating Venus-like exoplanets. *J Geophys Res Planets* 2020;125(5):e2019JE006276. doi.org/10.1029/2019JE006276
- Whitman WB, Coleman DC, Wiebe WJ. Prokaryotes: The unseen majority. *P Natl Acad Sci* 1998;95(12): 6578–6583. doi.org/10.1073/pnas.95.12.6578

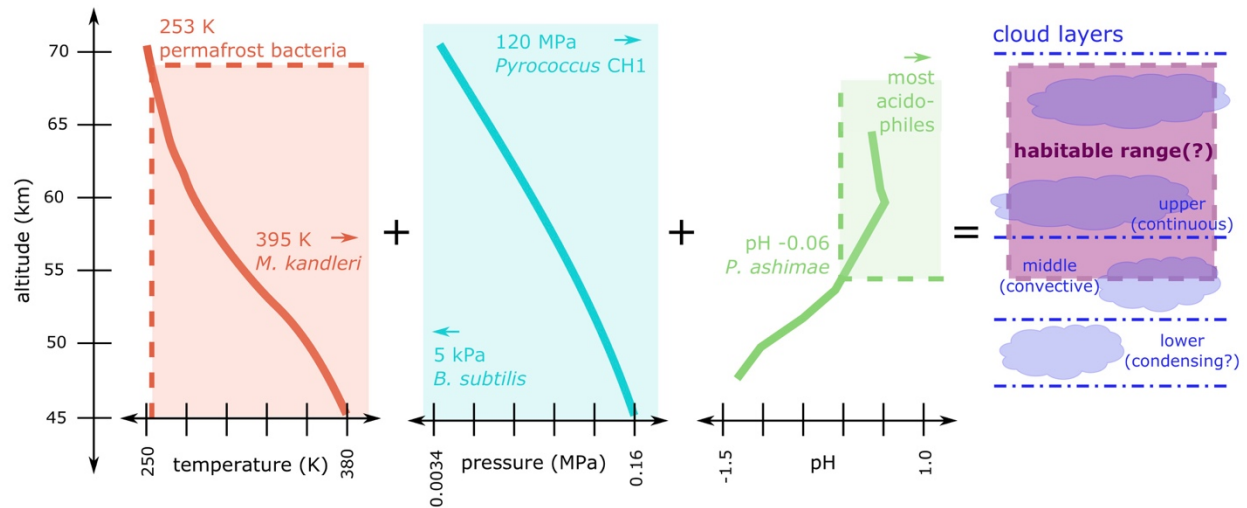


Figure 1. Three factors for which reasonable constraints exist that may point to favorable habitability conditions in the middle Venus atmosphere. Shown are upper and lower limits of temperature, pressure and pH prevailing in Venus clouds in the height range 45-70 km from its surface in the context of selected limit values for terrestrial life. Future missions may help to constrain additional major habitability variables such as water availability and ultraviolet radiation flux in this altitude range.

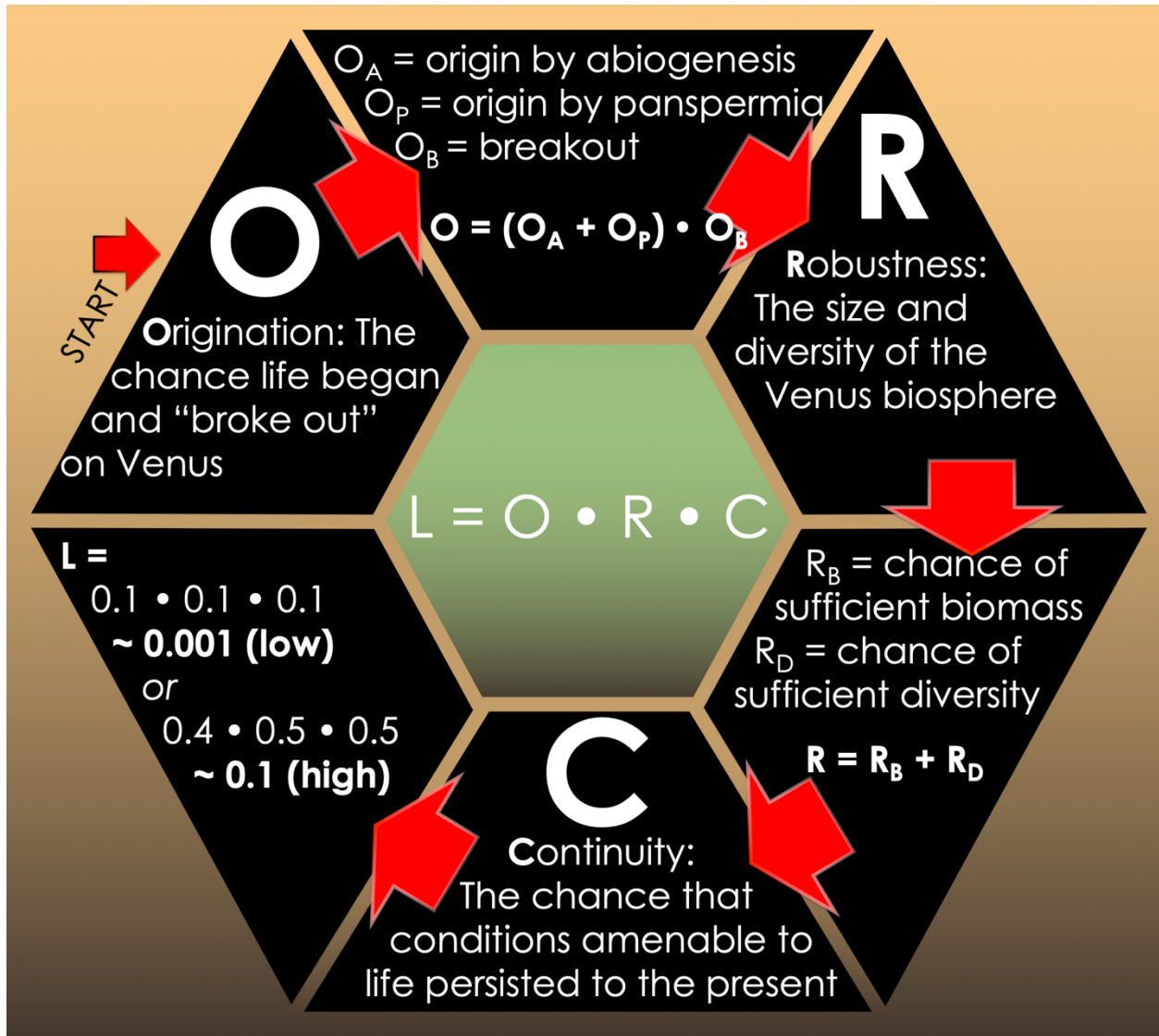


Figure 2. Schematic of the Venus Life Equation. Variables and equations elaborated in text. The final estimate for L in this figure represents an example low and high range of estimates for each factor.

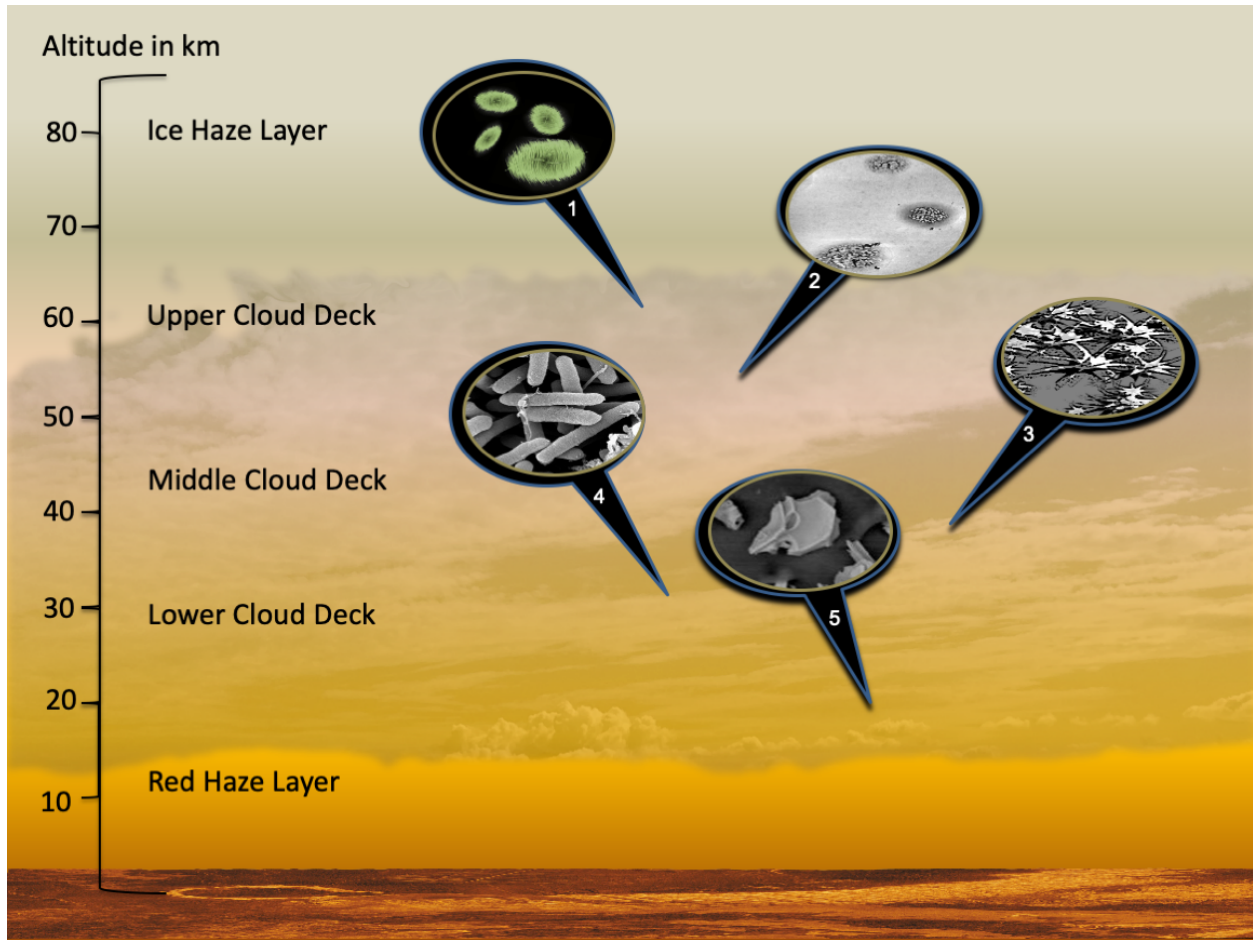


Figure 3. Notional particles potentially to be encountered in the Venus cloud decks, inspired by terrestrial atmospheric sampling, to guide future instrument and analysis selection: 1) Complex shapes with fluorescent properties, 2) Particulate aggregates of sulfates and related compounds, 3) Unidentified group of complex shapes adhered to an aerosol particle, 4) Objects that resemble Earth bacteria or archaea, and 5) volcanic ash particles.