PROBABILITY OF PLANETARY LIFE: THE VENUS LIFE EQUATION AND UNKNOWNS FOR OTHER WORLDS.

D. M. Gentry[1], N. R. Izenberg[2], M. Gilmore[3], D. Grinspoon[4], M. Bullock[5], P. Boston[1], Grzegorz P. Słowik[6] [1]NASA Ames Research Center, Moffett Field, CA, USA [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA [3]Wesleyan University, Middletown, CT, USA, [4]NASA Headquarters, Washington, DC, USA, [5]Southwest Research Institute, Boulder, CO, USA, [6]University of Zielona Góra, Zielona Góra, Poland.

Introduction: One of the greatest motivators for continued space exploration – whether crewed, robotic, or observational – is to understand the origin, distribution, and future of life in the universe. Although we are currently limited by the *n=1* problem of having Earth-based life as our only concrete example, we can nevertheless use our understanding of the genesis and evolution of life on Earth to establish a framework for identifying the unknowns and uncertainties of life on other worlds.

In 2021, we proposed the Venus Life Equation [1]. Inspired by the Drake Equation, the Venus Life Equation (VLE) is a theory and evidence-based approach to calculating the likelihood of extant life on Venus using three high-level parameters: Origination, Robustness, and Continuity, or $L = O \bullet R \bullet C$. As each of these factors changes over time, they also provide a framework for understanding the likelihood of life at a given point in time – including the future.

The fundamental goal of the VLE is to provide a scaffold for estimating the chance of life based on factors that can be constrained or quantified through observation, experiment, and modeling. Here, we review the existing framework as applied to Venus, and discuss some of unknowns and future work needed to extend this approach into a more general Planetary Life Equation.

The Venus Life Equation: Our interest was initially sparked by Venus because of its initial similarities to, followed by its dramatic divergence from, the surface conditions of Earth. Though our understanding of the past and present climate of Venus continues to evolve, it is believed that Venus had an early wet period where land-water interfaces similar to those of the late Hadean and early Archean Earth existed for an extended period of time; critically, this is also the window in which life on Earth arose. Venus's current surface (450 ºC, 92 bars) is not hospitable to life as we know it, although there has been much discussion of whether the sulfuric acid cloud layers could host a remnant aerobiosphere.

The VLE's terms are *L*, the likelihood of there being life at the time in question; *O* (origination), the chance of life arising and becoming established prior to the time in question; *R* (robustness), the potential size and diversity of the biosphere over time; and *C* (continuity), the chance that conditions amenable to life persisted spatially and temporally until the time in question. It is intentionally agnostic to the scale and type of life. All factors are treated as qualitative likelihoods, where 0 represents ''no chance'' and 1 ''a certainty''.

Origination: Factors to consider in estimating *O* include:

- the likelihood of origin by abiogenesis
- the likelihood of origin by panspermia, informed by the likelihood of life elsewhere in the star system and the dynamics of interplanetary matter transport
- the chances of two or more separate geneses (e.g., both abiogenesis and panspermia occurring)
- the chance of *breakout*, or life expanding beyond its point(s) of origin to occupy the planet

The chances of abiogenesis (either on the planet in question, or on a neighboring body as part of a panspermia hypothesis) are currently most often discussed through analogy to early Earth, informed by modeling and benchtop experiments. The breakout subfactor is the hardest to quantify; very little is known about the early history of life on Earth other than that it appears to have begun and spread relatively quickly after its surface became clement. This factor is therefore likely to be low for planets very early in their history, but to become and remain higher for Earth-like planets for most of their existence. Unlike the other two factors, which continuously fluctuate over time, this factor

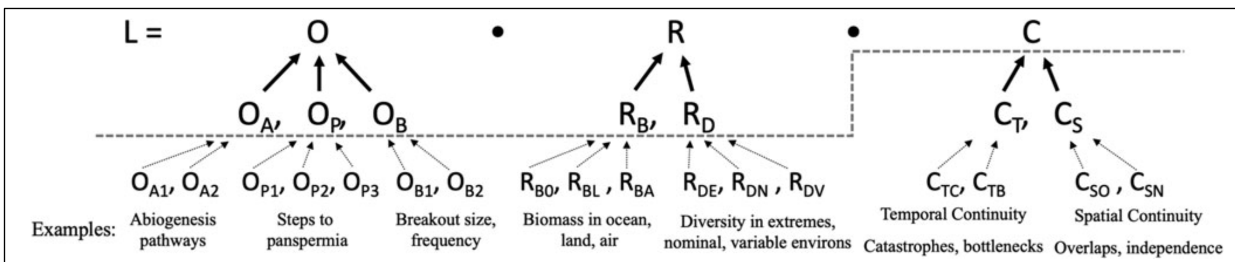

Fig 1. *Breakdown of the Venus Life Equation into a non-exhaustive set of subfactors. The dotted line indicates the scale at which current knowledge supports quantitative discussion for Venus and Earth.*

reaches 1 if life emerges and remains there. (If one is interested in separately calculating the likelihood of an independent genesis at a given point in time, or life re-arising after extinction, this factor can be treated as a separate equation with the same subfactors recalculated for the planet's current state.) For modern Venus, given its past similarity to early Earth, we considered *O* to have a range of 0.1 – 1.

Robustness: Factors to consider in estimating *R* include:

- the potential "best case" biomass supported over time, informed by the availability of essential nutrients (e.g., CHNOPS for Earth-like biochemistry) and energy (photonic, chemical, thermal) for primary production
- the functional diversity of life present (e.g., breadth of habitats occupied, ecological niches defined, metabolic strategies used)

A low *R* value indicates a small or fragile biosphere more vulnerable to extinction from the threats captured in the final *continuity* term. The supportable biomass for a planet can be informed by assumptions about likely biochemistry and habitats, which in turn informs analog, modeling, and experimental investigation of constraining energy, nutrients, and substrate. The functional diversity of life does not currently have an equivalent accepted metric; taxonomic diversity may be a usable, if imperfect, proxy, or other measures such as number of independent nutrient cycles may be developed as ecosystem modeling continues to advance.

Life on Earth has been widespread and diverse enough to persist through a number of mass extinction (bottleneck) events, including asteroid impacts and global glaciation – some of which occurred quite early in its history. Earth may not even represent a maximal biosphere (i.e., there may be planets *more* habitable than Earth). This factor is therefore likely to be high for planets similar to Earth between its Archean and current states. For modern Venus, given its inclement surface but suggested cloud habitability, we considered it to have a range of 10^{-7} – 0.1.

Continuity: Factors to consider in estimating *C* include:

- stellar lifetime and stability, such as coronal mass ejections
- planetary orbital stability
- planetary geological stability, such as resurfacing, long-term nutrient cycling, or climate-disrupting volcanism
- likelihood of major impact events, ranging from climate-disrupting (e.g., Chicxulub) to possible planetary loss (e.g., Theia)
- planetary climate history and stability, such as delivery, availability, and loss of water (for a water-based biochemistry)
- biogenic (life-caused) instability, such as the catastrophic shift in Earth's ocean and mineral chemistry as a result of oxygen buildup after the emergence of oxygenic photosynthesis

Some of these factors are relatively well understood (stellar lifetime, planetary orbits, impact probabilities). Others are ongoing areas of active research, primarily modeling informed by laboratory and field data. Biogenic instability is the most difficult to capture, as it depends on many assumptions about potential biochemistries, nutrient fluxes, and even potential technological developments that in turn rest on complex and poorly understood system dynamics.

A value of 0 for *C* indicates that there has been at least one total extinction event between the point in time of the *origin* event (including breakout) and the time being assessed. This has not happened on Earth to the best of our knowledge, although given the extreme sparsity of data on early Earth, there is currently no way to distinguish whether there has been a continuous history of life, or whether life arose independently several times or concurrently on early Earth but only one lineage survived to become established. For modern Venus, given the high uncertainty about its water and surface history, we considered it to have a generous range of 0.1 – 1.

Conclusions: The original Venus Life Equation is adaptable to a framework for guiding discussion about the past, present and future likelihood of life on a given planet. Working through the subfactors of each term can be further helpful in identifying and prioritizing research areas.

Two of the main challenges to expanding the VLE into a more general Planetary Life Equation are the current lack of quantitative metrics for biosphere robustness and the lack of a general framework for qualifying planetary climate stability over time. We look forward to addressing these and other challenges, and to input and feedback from the astrobiology community.

References: [1] Izenberg, N.R. et al. 2021. The Venus Life Equation. *Astrobiology*. 21, 10 (Jan. 2021), 1305–1315. DOI: 10.1089/ast.2020.2326.