THE VENUS LIFE EQUATION. N. R. Izenberg[1], D. M. Gentry[2], D J. Smith[2], M. S. Gilmore[3], D. Grinspoon[4], M. A. Bullock[5], P. J. Boston[2], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, (noam.izenberg@jhuapl.edu), [2]NASA Ames Research Center, Moffett Field, CA, USA, [3]Wesleyan University, Middletown, CT, USA, [4]Planetary Science Institute, Washington, DC, USA, [5]Science and Technology Corp., Boulder, CO, USA.

Introduction: Does life currently exist, or did life once exist, on other worlds in our solar system? The proximity of the rocky planets of our solar system, Venus and Mars, make them obvious targets for the first attempts to answer these questions via direct exploration, with concomitant implications for, and input to, how we think of exoplanets. Given the limited resources we have to explore our neighbors in space, an ecological assessment (based on terrestrial ecosystem principles) might help us target our search and methodology.

Studies of extreme life on Earth consistently reveal adaptability. Mars has been the target of many life-related investigations [1, many others]. Venus has not, yet there may be compelling reasons to think about extant life on the second planet [2], and lessons to learn there about searching for life elsewhere in the solar system and beyond.

The Venus Life Equation: Venus may have been habitable for billions of years its history and may still be habitable today. Our current state of knowledge of the past climate of Venus suggests that the planet may have had an extended period – perhaps 1-2 billion years – where a water ocean and a land ocean interface could have existed on the surface, in conditions possibly resembling those of Archaean Earth [3]. At present, Venus' surface is not hospitable to life as we know it, but there is a zone of the Venus middle atmosphere, ~55 km altitude, just above the sulfuric acid cloud layer, where the combination of pressure, temperature, and gas-mix are more Earthlike than anywhere else in the solar system [2, 4]. The question of whether life could have – or could still – exist on the Earth's closest neighbor is more open today than it's ever been.

Here we approach the question of present-day life on Venus in a manner analogous to the Drake Equation [5], treating the possibility of current Venus life as an exercise in informal probability – seeking qualitatively the likelihood or chance of the answer being nonzero.

The working version of the Venus Life Equation is expressed as:

$$L = O * P * A * S$$

where L is the likelihood (zero to 1) of there being life on Venus in the present-day (including the planet's atmosphere), O (origination) is the chance life ever began on Venus, P (proliferation) is the chance life filled the minimum critical niches that must be filled for a biosphere to be self-sustaining on Venus, A (adaptation) is the probability life could evolve as fast as or faster than conditions on the surface became uninhabitable, and S (stability) is the chance that there are sufficient essential accessible ingredients in some Venus environment to sustain life processes today. The Venus Life Equation is a work-in-progress as a pre-decadal White Paper [6] and its variables are currently being refined.

Origination. Life on Venus could have originated in one of two ways: independent abiogenesis, or importation from elsewhere (panspermia - the most likely candidate being Earth), which could be termed subfactors O_A and O_P respectively. However, is O the sum of those subfactors, or instead the net probability that life originated either way (e.g. $O = 1- ((1- O_A) * (1- O_P))$? Whether life originated on Venus independent of Earth depends on how "easy" abiogenesis is under the relevant conditions, or in other words: is O_A a trivial number (perhaps less than 0.0001 over solar system history?) a significant possibility (0.1 or greater?), or something in between?

Proliferation. Earth is brimming with life. Everywhere we look for it, from deep ice cores to highest mountains to deep sea vents, hyper-arid deserts, acidic springs, deep caves, extremophile life fills nearly every niche we can examine, when 'standard' life does not. The most notable current exception is Earth's atmosphere; while many microorganisms spend *parts* of their life cycle airborne, no terrestrial life has yet been found that conducts its entire life cycle (growth, survival, reproduction) in the air. How long did it take for all of Earth's niches to be filled? How about Venus? To answer this, we need to understand more about the ancient environments on Venus and life in Archean/Proterozoic Earth.

Adaptation. Life on Earth has survived many major, and some near global extinction events. How can we quantify the chances that life has been able to adapt to massive changes in its environment? In the case of Venus, the essential question is whether life could evolve the functions necessary for either survival on the surface or permanent residence in the atmosphere as rapidly as runaway heating and loss of water occurred? For this we need to understand the history of water and its loss on Venus, through measurements like D/H ratio [7].

Stability. This factor depends on the potential planetary niche-maintaining availability of the resources required by life processes (*e.g.*, for terrestrial life, the elements C H N O P and S), the availability of a solvent in which reactions can take place, and an environment that is protected enough from destructive heat/cold/radiation, etc. Available energy or sufficient energy gradients for life processes are part of this factor as well.

Each of the Venus Life Equation factors and subfactors can be estimated with greater or lesser confidence. The first iteration of the equation (see [6] for details) resulted in

$$\boldsymbol{L} = 0.5 * 0.6 * 0.5 * 0.2 = \mathbf{0.03}\ \textit{(low)}\ \text{or}$$
$$\boldsymbol{L} = 0.5 * 0.8 * 0.5 * 0.5 = \mathbf{0.1}\ \textit{(high)}$$

or a 3% to 10% chance life exists today on Venus (most likely in the upper troposphere (define ~altitude range)). Whether the assumptions or variables are realistic and where they fail are subjects for discussion and debate. However, results like this for Venus motivate, and may be tools to justify new avenues of research and calls for direct measurements. For example, direct measurement of elemental ratios and materials escaping the Venus atmosphere will give more clues about the ancient atmosphere and thus the history of water and conditions on the ancient surface, affecting factors *P* and *A*. In-situ measurements of the composition and environment in the Venus atmosphere and clouds can put real constraints on *S* and drive the entire Venus Life Equation towards zero (if we find some essential ingredient completely missing, or as high as 20%.

Implications and Speculations: The first cuts at the Venus life equation imply that life could have been both present and abundant at least until its oceans were lost. Just as the ocean/fluvial environment may have left signs within the planet's geology and composition that new missions could identify (*e.g.*, higher resolution radar imaging, direct imaging near the surface, chemical and mineralogical analysis of surface materials), so too could life have left markers for us to find – in geologic strata as fossils, in chemical/elemental ratios, etc. These kinds of observations are all within our technical capabilities today. Thus, new missions to Venus, even if they do not directly search for life, can significantly improve our understanding of the planet's early conditions, whether life ever arose there, or could have survived until today.

Further, if we do decide to search for Venus life directly, initial discussions on origination suggest that looking for signatures of or similar to terrestrial (likely extremophile) biology may be a reasonable, even logical approach.

Finally, each of the factors used for Venus can be adapted, possibly with different or additional subfactors, to a more generalized Planetary Life Equation [8]. For example, generalizing beyond Venus, within the solar system near to Earth we can debate whether we *need* a separate start to life or whether panspermia (presumably from early Earth, but cases can be made for life originating elsewhere in the solar system) is a reasonable probability – likely with O_P decreasing the farther you get from home. For exoplanets, unless we want to talk about interstellar panspermia, O must rely on O_A not being infinitesimal.

For the solar system's ocean worlds, or for exoplanets, *S* may have similar or very different subfactors; life on exoplanets may indeed not be life as we know it, and may require different resources.

In this most general case, the $\boldsymbol{L}$ in the Planetary Life Equation is necessary to solve for $\boldsymbol{f_l}$ of the Drake Equation: the fraction of planets in our galaxy that actually develop life [5]. The Venus Life Equation is currently being refined; *e.g.* the current iterations of factors *P* and *A* may not be completely independent as variables. However, the working version of the equation for Venus does give a blueprint for adaptation to other worlds.

Acknowledgements: This abstract builds on this group's ongoing work for the Venus Life Equation pre-Decadal White Paper, which also includes G. Slowik, University of Zielona, Gora, Poland

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