THE PLANETARY LIFE EQUATION. N. R. Izenberg, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, (noam.izenberg@jhuapl.edu)

Introduction: One of the biggest questions of, and motivators for, exploring the solar system and beyond is whether life currently exists, or now-extinct life once existed, on worlds beyond ours. Given the proximity of the rocky planets of our solar system, Venus, Mars, and the most extreme environments of Earth are obvious targets for the first attempts to answer these questions via direct exploration, with concomitant implications for how we think of exoplanets.

Studies of extreme environments on Earth have shown just how adaptable is life as we do know it. Mars has been the target of many life-related investigations. Venus has not, yet there may be compelling reasons to think about extant life on the second planet, and lessons to learn from there about searching for life elsewhere in the solar system and beyond.

Precursor - The Venus Life Equation: Our current state of knowledge of the past and present climate of Venus suggests that the planet may once 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 [1]. Also, although today Venus’ surface is far from 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 more Earthlike than anywhere else in the solar system [2]. 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.

What if we approached the question of present-day life on Venus in a similar manner as Drake Equation [3], treating the possibility of current life on Venus (including the planet’s atmosphere in the word “on”) 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:

\[ L = O \times P \times A \times S \]

where \( L \) is the likelihood (zero to 1) of there being life currently in some Venus ecosystem, \( O \) (origination) is the chance life ever began on Venus, \( P \) (proliferation) is the chance life filled all available, or all critical ecological niches on Venus before conditions began to become increasingly hostile, \( A \) (adaptation) is the probability life could evolve as fast as or faster than conditions on the surface became, to terrestrial reckoning, 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 an ongoing pre-decadal White Paper project [4] and its variables are currently being refined. For example, life on Venus could have originated in one of two ways: independent abiogenesis, or importation from elsewhere (pansperva – the most likely candidate being Earth), which could be termed subfactors \( O_s \) and \( O_r \) respectively. However, is \( O \) the sum of those subfactors, or instead the net probability that life originated either way (e.g. \( O = 1- ((1- O_s) \times (1- O_r)) \)).

Whether life originated on Venus independent of Earth depends on how “easy” is abiogenesis, or in other words: is \( O_s \), a trivial number (less than 0.0001?) a significant possibility (0.1 or greater?), or something in between?

Each of the other Venus Life Equation factors similarly comprises subfactors. The first iteration of the equation (see [4] for details) resulted in

\[ L = 0.5 \times 0.6 \times 0.5 \times 0.2 = 0.03 \text{ (low)} \]
\[ L = 0.5 \times 0.8 \times 0.5 \times 0.5 = 0.1 \text{ (high)} \]
or a 3% to 10% chance life exists today on Venus (most likely in the upper troposphere). 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 help justify new avenues of research and calls for direct measurements of the planet in new missions. For example, the stability factor \( S \) depends on subfactors like the availability of the resources required by life processes (e.g., for terrestrial life, the availability over time of 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, and others. In-situ measurements 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 and \( S \) goes to zero), or as high as 20% (if all ingredients are there in abundance and \( S \) approaches 1).

**Planetary Life Equation**: Each of the factors used for Venus can be adapted, possibly with different or additional subfactors, to a more generalized Planetary Life Equation. For example, generalizing beyond Venus, but still 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 \( O \), decreasing the farther one gets from home. For exoplanets, unless we want to talk about interstellar panspermia, \( O \) pretty much must rely on \( O \), not being infinitesimal.

Additionally, for our solar system’s ocean worlds, or 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 Planetary life equation’s four main factors are the same as for the Venus Life Equation. The \( L \) in the Planetary Life Equation now also helps solve for \( f \) of the Drake Equation: the fraction of planets in our galaxy that actually develop life [4]. While 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), the working version of the equation for Venus provides an early blueprint for how we might reasonably estimate the probabilities for life on other worlds.

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**References**: