AEROBIOSPHERES AND PLANETARY HABITABILITY: CONSIDERATIONS FROM EARTH TO VENUS AND BEYOND. D. M. Gentry[1], L. Iraci[1], A. Cassell[1], A. Mattioda[1], A. Brecht[1], K. Simon[2], P. Sobron[2], A. Davila[1]. [1]NASA Ames Research Center (diana.gentry@nasa.gov), [2]Impossible Sensing.

Introduction: "Follow the water" has long been a guiding theme of astrobiological exploration. Terrestrial (rocky) worlds with water are likely to have clouds, yet the possibility of aerobiospheres – long-term stable airborne habitats, analogous to frozen cryobiospheres or hydrobiospheres – is rarely discussed.

Earth's clouds carry a significant presence of metabolically active microbes [1]. Inactive microbes, or dead microbial debris, further comprise a significant minority of dry dust [2], extending through the troposphere and into the stratosphere. However, the most favorable (warmest and wettest) cloud environments on Earth are also the most transient. We have not yet observed airborne microbial reproduction in the field, and one likely reason is that microbes on Earth do not stay airborne for very long compared to typical generation times.

Even so, Earth's airborne microbiology is significant at a planetary scale. Effects include weather (microbes as condensation and ice nuclei), climate (alteration of cloud and surface albedo), and water and air chemistry (through metabolic processing) [3]. Some of these effects, if present on exoplanets, could be detectable through remote observation. Evaluating the parameters that constrain cloud habitability can therefore help us understand not only Venus's past and present habitability, but also the broader search for life in the universe.

Physical Constraints: The physical requirements for terrestrial life (or "life as we know it") are often categorized as: (1) water, as the overall solvent; (2) nutrients – C, H, N, O, P, S, and trace elements, the most significant of which is Fe; (3) an energy source, usually a combination of chemical and photonic; and (4) a generally stable environment, without too much or too little heat, pH, radiation, etc. We limit the discussion below to these terrestrial requirements and to water clouds on rocky worlds, but it is worth noting that if considering the potential of alternative (non-water and/or non-carbon) biochemistries, much of the same reasoning would apply to non-water clouds like those of Titan or Triton.

Table 1: *Typical population densities of Earth's airborne microbes.*

	population density
troposphere (dry air)	$10^4 – 10^8$ m^{-3} (over land) $10^1 – 10^6$ m^{-3} (over sea)
troposphere (clouds)	$10^4 – 10^8$ mL^{-1} $10^{-2} – 10^{-9}$ $droplet^{-1}$
stratosphere	$< 10^1 – 10^6$ m^{-3} (viable but inactive)

Water availability is particularly important in aerobiology. (If the water is mixed with another solvent, as in Venus's sulfuric acid cloud and haze aerosols, *water activity* – a measure of the amount of energy required to extract water from the environment – may be limiting instead.) Earth's atmosphere is generally not water-saturated, so under most conditions, the majority of aerosolized microbes are rapidly, and fatally, desiccated. Airborne regimes that lead to cycles of dehydration and rehydration are even more damaging, as biomolecular damage incurred during the process of drying out can accumulate faster than microbes are able to repair it during their wet, active stages. Only a few classes of desert microbes are known to have the adaptations necessary to tolerate rapid desiccation cycles well, even on the ground [4].

However, warm, low-altitude clouds are, from a biological perspective, roaming water 'hot spots'. In fog and cloud droplets, suspended microbes may stay hydrated and metabolically active as long as the cloud persists. Although ice clouds are less well studied, it is well-known that many strains of microbes can remain active several degrees below 0 ºC, and some liquid water remains available at ice grain boundaries and other particle microenvironments down to –40 ºC.

Interestingly, several microbes known to tolerate aerosolization, including airborne freezing, have surface properties that trap liquid water, making them particularly effective nuclei for cloud formation at lower humidities [3]. These adaptations are believed to have originated as protection against surface desiccation, but show that even in relatively sparse airborne habitats, life's ability to alter its own local microenvironment remains important.

Nutrient availability corresponds to the basic elemental building blocks of life, which must be present in forms that life is capable of using (particularly important for carbon, phosphorus, and nitrogen). Nutrient levels in clouds are primarily driven by surface fluxes and mixing dynamics.

Unless a nutrient is effectively absent from an environment, low nutrient levels are likely to slow or limit population growth rather than prevent inhabitation entirely. On Earth, nutrients in fog and cloud water are similar to those in sparsely inhabited lakes (**Table 2**). Though there are substantial differences between land and marine cloud water sources, and large swings

Table 2: *Major bioavailable nutrients, typical levels in cloud water, and typical levels in oligotrophic (sparsely inhabited) lake water for comparison.*

Nutrient	***Cloud Water (g/L)***	***Lake Water (g/L)***
DOC	$0.3 - 6 \times 10^{-3}$	$1 - 5 \times 10^{-3}$
NH_4^+	$0.3 - 2 \times 10^{-2}$	2×10^{-5}
NO_2^-	$0.03 - 2 \times 10^{-3}$	6×10^{-6}
NO_3^-	$2 - 6 \times 10^{-3}$	$0.7 - 3 \times 10^{-5}$
PO_3^-	$0.0.2 - 1 \times 10^{-4}$	$2 - 7 \times 10^{-5}$
SO_4^{-2}	6×10^{-2}	1×10^{-3}

following major weather events, this implies that if Earth clouds were longer-lived, their habitability might still be ultimately constrained by the amount of biomass that could be supported by typical nutrient levels. This phenomenon can be generalized to a required balance between growth rates and residence times, as discussed below.

Energy availability, as a constraint, functions similarly to nutrient availability. While there are theoretical lower bounds on available energy for habitability, in otherwise habitable environments, low levels of bioavailable energy typically translate to a slower-growing population. In turn, this may lower the robustness of the biosphere to climate change or long-tail extinction-level events. Earth aerobiology usually has ample photo-synthetically-active (400-700 nm) radiation available, and levels are broadly similar in Venus's cloud layers [5].

Environmental stability in aerobiology includes a unique threat: gravity. Cell-size particles (or cell aggregates) can stay airborne indefinitely only under a very narrow range of conditions. The *settling rate,* or rate at which particles 'fall out' of the air, is determined at the microscale, by a combination of gravity, air density and viscosity, effective radius, and electrical charge. The mean length of time a particle remains airborne, or *residence time*, is further affected by larger-scale phenomena, including thermal lofting, gravity waves, scavenging due to precipitation ('raining out'), and turbulence. On Earth, microbe-scale particles (0.2 - 1 μm) in the clement troposphere have residence times of hours to days [6], though particles which have been injected into the far less hospitable stratosphere may endure for months or more.

Biological constraints: For a biosphere to be stable over the long term, its population gains must outweigh its losses. Habitability of a (cloudy) atmosphere therefore goes beyond survival of individual organisms to a higher-level constraint derived from the constant losses to gravity: the reproduction rate of the population must be faster than the settling rate ($r_r > r_s$), or, conversely, the overall mean generation time must be less than the overall mean residence time ($t_g < t_r$).

This constraint is the most likely explanation for why we have not yet observed airborne microbial reproduction in the field, despite promising laboratory evidence. The hardiest microbes most likely to be active while airborne – those able to continue to grow despite low temperatures, low nutrient rates, potential periods of desiccation, and higher-than-usual irradiation – also typically have generation times of days or even weeks, exceeding typical Earth cloud durations.

This constraint becomes even stricter when environmental variability and the presence of other stresses (pH, temperature, radiation, etc.) are taken into account. During inactive periods, biomolecular damage continues to accumulate, and will eventually reach a threshold where the organism is unable to repair itself even after being restored to a clement environment.

Implications for Venus: Early Venus and Earth may have been similar in surface geochemistry, rock/water interfacing, and geothermal activity: during factors associated with the emergence of Earth-like biochemistry. Could Venus have had past water- and carbon-based life, and could have persisted to the present day in Venus's sulfuric acid cloud and haze layers, which hold much of Venus's remaining water? Investigations of these questions have also been connected to disequilibria in atmospheric sulfur chemistry [7], strong atmospheric UV absorption [8], and the controversial recent claim of phosphine detection [9, 10].

Earth's atmosphere is stratified, and its various environments can provide only partial analogues for the Venus cloud layer – tropospheric clouds are shorter-lived and wetter, and stratospheric sulfate aerosols are colder and smaller. However, experience exploring their microbial and organic presence suggests some important considerations for future habitability or life detection missions to Venus's atmosphere.

Science Questions: Basic environmental (T, P, γ, redox) and chemical requirements for life are believed to be met in the Venus cloud aerosols. Water activity and acid activity are the two most significant unknowns. If current estimates of overall Venus aerosol composition are correct at >85% H_2SO_4 / H_2O, then the corresponding water activities are far below any environment on Earth where metabolic activity has been observed [11], and the acid activity is at least at high as Earth hydrothermal systems which have been sampled and found to be barren [12].

However, small changes in minor constituents can have significant changes on effective activities, and the detailed composition of Venus aerosols are not well constrained. More generally, a dynamic atmosphere – especially one subject to variable surface influxes, such as dust storms, volcanism, or meteoritic infall – will have local, transient, or sparse microenvironments that depart significantly from the mean values captured by bulk measurements. The example given above for liquid water in ice cloud particles well below the 'bulk' temperature limit for water availability is a good example; others observed in Earth microbiological habitats include self-shading of cell aggregates as protection from irradiation, passive and active surface transporters that sequester particular nutrients or maintain osmotic balance, and direct alteration of local water and gas chemistry through metabolism. Diurnal, seasonal, and other dynamics in Venus aerosol composition are poorly understood, let alone detailed particle-level physical phenomena.

Technological Concerns: Life in extreme conditions is typically highly heterogeneous down to very small scales, with most biomass inactive and clustered in 'hot spots'. This is especially true of Earth bioaerosols, whose density and relative concentration can vary in space and time over several orders of magnitude (**Table 1**).

Depending on the current size of cloud particles and the tendency of particular cell types to cluster, a life detection mission to Earth's clouds might encounter a ratio of 'particles of interest' ranging between 10^{-2} – 10^{-9}. Sensitivity across such a large range is a significant challenge for many instruments. This is especially true for mission concepts that require sample analysis at high cadence due to fast travel (e.g., descent probes) and limited operations time (e.g., due to short surface lifetimes on the surface). When choosing an aerosol sampling strategy, it is important to bear in mind that single transects, or even balloon-based platforms which follow single air masses, may therefore not yield representative data.

Recommended Observations: The targets in **Table 3** cover significant bioavailable nutrients, water and acid, major compounds that may affect water and acid activity, and specific molecular signatures associated with organics; they can also be captured with low-cost, low-mass optical instruments (e.g., Raman, TLDS, LIBS, LiDAR). A small instrument suite capable of measurements at fast cadence could allow multiple passive small sondes to be deployed alongside a large, higher-resolution descent probe or lander mission architecture. This strategy reduces the risk of missing 'hot spots' of interest, while also offering more detailed atmospheric distribution and dynamics information.

Table 3: *Suggested elemental and molecular targets for constraining Venus aerosol habitability.*

	target
elemental	S, H, C, H, P, Cl, N, O, Fe
molecular	H_2O, H_2SO_4, SO_x, PO_x, NO_x, NH_x, CH_x
specific	organic moieties (C=C, C=O, C≡N, ...)

Knowledge gaps: There is a clear need for co-ordination between atmospheric modelers, especially in cloud microphysics, and microbiologists, especially in aerobiology. Key questions include:

- For microbe-sized particles, what observations are required to estimate typical residence times, trajectories, and hydration cycles in planetary atmospheres?
- For microbes which tolerate repeated desiccation, irradiation, and other airborne stressors, what are typical generation times? How are these affected by limitations on bioavailable nutrients and energy? Which factors are most limiting?
- How long can such microbes remain viable while inactive under combinations of accumulating stressors (high UV, varying RH, low temperature, etc.)? Which factors are most limiting?
- How do the answers combine to constrain the habitability space of potential cloudy worlds? How well do these constraints map to Earth, Venus, and potential exoplanets?

The biology of Earth's atmosphere is significantly underexplored, especially compared to its land, oceans, and even subsurface biospheres. Field, lab, and modelling work must be combined to address these basic questions. The results will help us understand the extent of life on Earth, past and present Venus habitability, and the potential for life elsewhere in the universe.

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