CLOUD HABITABILITY FROM EARTH TO VENUS: SCIENCE & TECHNOLOGY CONSIDERATIONS.

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Introduction: Early Venus and early Earth are believed to have shared many aspects associated with the emergence of an Earth-like biochemistry: surface geochemistry, rock/water interfacing, and geothermal activity. There is significant interest in whether such life – based on water and carbon – could have persisted to the present day in Venus's sulfuric acid cloud and haze layers, where some liquid water remains. Investigations of this possibility have been connected to understanding observations such as disequilibria in atmospheric sulfur chemistry [1], strong atmospheric UV absorption [2], and the controversial recent claim of phosphine detection [3, 4].

Earth's atmosphere contains a substantial and active microbial presence [5], primarily in tropospheric cloud water but also in dry aerosols extending through the stratosphere. These environments are only partial analogues for the Venus cloud layer – tropospheric clouds are shorter- lived and wetter, and stratospheric sulfate aerosols are colder and smaller – but 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 present in the Venus cloud aerosols. Water activity and acid activity are the two most significant unknowns. If current estimates of >85% H_2SO_4 / H_2O are correct, then the corresponding water activities are far below any environment on Earth where metabolic activity has been observed [6], and the acid activity meets or exceeds Earth hydrothermal systems which have been found to be barren [7]. 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 or volcanism – will have local, transient, or sparse microenvironments that depart significantly from the mean assessed by bulk measurements. For example, on Earth, liquid water can persist in ice cloud particles at grain or surface boundaries down to –40 ºC, well below the 'bulk' temperature limit for water availability. Diurnal, seasonal, and other dynamics in Venus aerosol composition are poorly understood.

***Table 1:** Suggested elemental and molecular targets for constraining Venus aerosol habitability.*

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

Recommended Observations: Key suggested measurements for habitability assessment of Venus cloud and haze aerosols, including minor constituents, are shown in Table 1. These cover significant bioavailable nutrients, water and acid, major compounds that may affect water and acid activity, and specific molecular signatures associated with organics.

Understanding the distribution of these targets – for example, variability, or association with aerosols of a particular size mode, or with liquid or solid aerosol phases – is a key follow-on goal.

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. Depending on altitude, residence time, proximity to land, and other factors, cloud water may hold 10^2 - 10^8 viable cells per mL; depending on the typical size of cloud particles and tendency of cells to cluster, this can be equivalent to one viable cell per 10^2 - 10^9 aerosol particles. Sensitivity in the lower part of this range is a significant challenge for many instruments, particularly those that must operate at high analysis cadence. Single transects from descent probes, or even balloon-based platforms which follow single air masses, may therefore not yield representative data.

The targets in Table 1 can be achieved with optical instruments (e.g., Raman, TLDS, LIBS, LiDAR). A low-cost, low-mass suite capable of measurements at rapid cadence could allow multiple passive small sondes to be deployed alongside a large, higher-resolution descent probe or lander mission architecture, capturing additional distribution and dynamics information.

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