SUSTAINED *IN SITU* EXPLORATION OF THE HABITABILITY OF VENUS' CLOUDS. M. A. Bullock[1], J. S. Elston[2], M. Z. Stachura[2], S. Lebonnois[3], [1]Science and Technology Corp., mbullock75@gmail.com, [2]Black Swift Technologies, 2840 Wilderness Pl Ste D, Boulder, CO 80301, elstonj@bst.aero, mstachura@bst.aero. [3]Laboratoire de Météorologie Dynamique, Paris, msebastien.lebonnois@lmd.jussieu.fr.

Introduction: Direct sampling and analysis of Venus' clouds and atmosphere are necessary for understanding how cloud processes, radiation, and dynamics are coupled on that planet. We discuss how an aircraft can harvest energy in Venus' atmosphere for sustained flight and perform *in situ* scientific experiments around the planet.

Flight in the Clouds of Venus. By dipping into and out of the shear layer at around 60 km, a specifically designed aircraft can stay aloft in Venus' atmosphere without expending energy, much the way an albatross can cross the ocean without flapping its wings [1] . The horizontal winds and vertical shear in Venus' atmosphere, from the IPSL Venus GCM at the equator, at midnight [2], is shown in Fig. 1. The red dashed line marks the vertical shear that is necessary for propulsion-less dynamic soaring for an aircraft with a ratio of coefficient of lift to coefficient of drag of about 50. Our design achieves a C_L/C_D of ~70. The shear layer at 60 km is present at all times of day at low latitudes, with shear strengths of > 10 m/s-km.

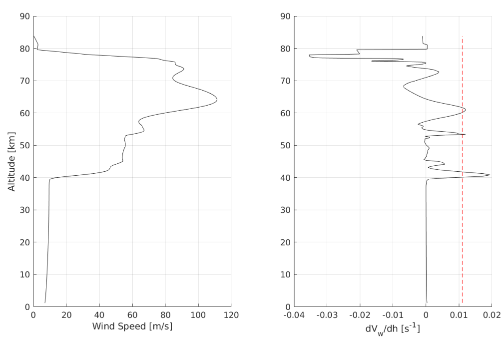

Figure 1. IPSL GCM winds and vertical shear at midnight at the equator, as functions of altitude [2]. The red dashed line marks the shear that is necessary for sustained dynamic soaring for an aircraft with a C_L/C_D of 50.

Sustained flight and high cadence of in situ measurements will be possible at 60 km, near the bottom of the upper cloud. Brief excursions to the shear layer at 40 km may be possible if sufficient energy can be extracted from the winds (Fig. 2). Chemical and aerosol measurements throughout the cloud column will then be possible. Geological mapping of the surface from below the clouds at near-IR wavelengths would provide a window on the surface that has never before been possible. Multicolor near-IR images of Venus' surface, without the intervening, scattering of the clouds, would enable broad swaths of Venus surface to be imaged at 20 m/pixel. This is 4 times the resolution of Magellan Synthetic Aperture Radar images that are available today [3]. The Magellan images are insufficient for resolving fundamental geologic relationships. Imaging at near-IR wavelengths from below the clouds would revolutionize our understanding of Venus' geology.

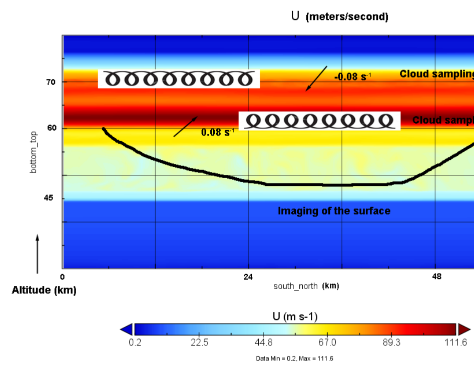

Figure 2. Possible dynamic soaring trajectories in Venus' atmosphere. Background color is wind speed. Dynamic soaring is accomplished by dipping in and out of the shear layer at ~60 km. Occasional forays below the clouds to image the surface may be possible.

Heritage. The Venus dynamic soarer inherits technology from the extensive body of work on autonomous UAV flight in the Earth's atmosphere [4,5]. Flight control algorithms have been developed to maximize energy in dynamic soaring environments [5]. UAVs from Black Swift Technologies have sampled volcanic gases in the air above Kilauea, Turrialba, and Makushin volcanoes. They are developing a system to make crucial meteorological measurements of hurricanes as they navigate autonomously through them.

Science Capabilities. An important advantage of fixed wing aircraft over other instrument platforms is its high degree of navigability. Dynamic soaring aircraft can be flown to specific features in the atmosphere of Venus to make measurements. For example, the tilted horizontal streaks in the clouds at mid-latitudes are most likely caused by baroclinic instability in this region of the atmosphere [6]. In situ wind and chemical heterogeneity measurements would reveal the nature of these disturbances, in addition to jets, and eddies.

Cloud Discontinuity. One special region of Venus' atmosphere is shown in Fig. 3, where a long-lived cloud discontinuity has developed, propagating faster than the superrotation [7].

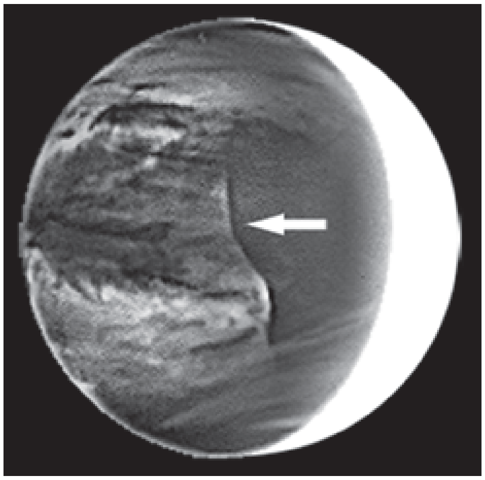

Figure 3. Lower cloud discontinuity from 2.26 µm images of the night side of Venus [2].

This feature has been seen almost consistently over 40 years. Mcgouldrick et al, 2021 [8] retrieved the cloud base altitude, aerosol acid mass fraction, below-cloud H_2O and CO, and the ratio of large to small particles on either side of the discontinuity, using VIRTIS-M spectral image cubes and the radiative transfer methods of Barstow et al, 2012 [9]. They found a rapid decrease in the cloud base, H_2O mixing ratio, and size parameter as the discontinuity front passed by. At the same time, the acid mass fraction increased across the discontinuity. These authors hypothesized that the discontinuity is caused by the passage of a 4.9 day Kelvin wave, causing an increase in the lower cloud thickness, lowering of the cloud base, and entrainment of small, acidic aerosols. The H_2O vapor abundance below the clouds also decreased as the front passed, consistent with its transport up into the clouds by the upwelling.

The aircraft can easily fly transects across the persistent cloud disruption region, sampling gases and aerosols and making meteorological measurements on either side of the discontinuity. A highly plausible explanation for this decades-old atmospheric feature is that it is the crest of an equatorial Kelvin wave that rotates around the planet even faster than the superrotation. With a phase speed of 20 m/s, it may even be possible, at the right altitude, to fly to and surf this wave around the planet.

Sustained in situ flight in Venus' clouds will answer the questions: How is the formation of the complex cloud patterns on Venus related to atmospheric dynamics? Do Kelvin and other planetary scale waves (mid-latitude Rossby waves) constrain the formation of Venus' clouds? And how are these related to the atmospheric superrotation, since the Kelvin wave has a positive phase velocity relative to the average zonal wind?

Unobscured radiance measurements. UV, visible wavelength, and IR radiance measurements, both down looking and upward looking, are crucial for understanding the energy balance of Venus' atmosphere, and constraining atmospheric constituents. Compared with a balloon platform, fixed wing aircraft can perform unobscured radiance measurements in all directions.

Search for habitability. Questions about the habitability of Venus' clouds can be answered by in situ measurements. Aside from environmental conditions that appear to favor life, recent reports have concluded that the high acidity and low water activity of Venus cloud aerosols are far outside the limits of life as we know it [10]. However, the composition of Venus' cloud aerosols is actually unknown, and it has been suggested that mineral buffers could raise the pH and water activity to such that life, even terrestrial life, could survive [11]. Aerosol mass spectroscopy, and simpler MEMS sensors for gas abundances in the atmosphere, could solve the question of the habitability of Venus clouds.

Scientific Payload. A dynamic soaring glider could stay aloft indefinitely, transecting the cloud discontinuity and characterizing the cloud particles and atmospheric gases across the cloud discontinuity.

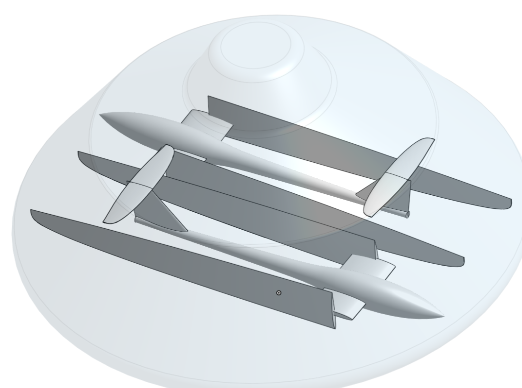

Figure 4. Two of the 6. 6m wingspan aircraft fit within an aeroshell, each possibly containing complementary payloads.

A minimal but scientifically useful payload would consist of atmospheric structure (pressure, temperature, accelerometers) and MEMS chemical sensors for parts-per-billion measurements of atmospheric gases. A single chip ultrastable oscillator would enable the accurate determination of position, using radio techniques from either Earth-based radio dishes or a relay probe in orbit around Venus.Such a payload would be ideal for the mass-constrained payload of a Venus aircraft. Together, these relatively powerful sensors would weigh less than a kilogram and consume less than 2 Watts. Our point design, with a 6.6 m wingspan, could carry a payload of up to 10 kg (Fig 4). For such a mission, a glider could also carry up and down-looking radiometers for a complete description of the radiation field in the clouds. In addition, specialized payloads could be flown in separate aircraft. A polarizing nephelometer that could provide constant data on the cloud aerosol size distribution, phase function, and indices of refraction of the particles. Alternatively, an aerosol mass spectrometer, recently developed at JPL [12] could measure all aerosol and atmospheric constituents to parts per trillion accuracy. A fluorescence microscope could look for organic molecules and determine their provenance (abiologic or from biology).

Operations. On the dayside, solar energy is plentiful at these altitudes, enough to operate scientific instruments, autonomously navigate, communicate, and charge batteries for night side operations. By flying with the zonal wind, the dynamic soaring glider spends only 2 days on the nightside, allowing continuous scientific measurements during both the day and night. Fig. 5 shows the available energy from triple junction solar cells on our design as a function of altitude [14]. The blue line shows the power produced from utilizing 80% of the 5.35 m^2 of surface area of the aircraft. The black line shows the power required for propulsive cruise versus altitude. Matched with 2.6 kg of Li-ion rechargeable batteries, the average power over night and day flight is approximately 110 W.

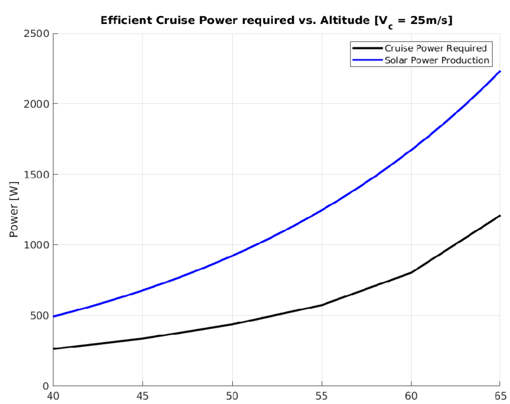

Figure 5. Available power from solar cells on a dynamic soaring aircraft in Venus' atmosphere (blue line). The required power for propulsive flight is shown by the black line.

Science Goals. Many challenging VEXAG goals and objectives [13] will require *in situ* sampling and analysis of the atmosphere and clouds. For example, The unknown UV absorbers, which have resisted remote measurements, will probably only be known when an aircraft or balloon can fly through the upper clouds. Similarly, the discrepancy of SO_2 and H_2O profiles between photochemical models and measurements will probably only be solved by direct sampling and measurements of the Venus cloud aerosols and atmospheric gases in many different locations.

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References: [1] Sachs, G., 2005. Ibis. 147, 1-10. [2] Lebonnois, S. et al., (2010), Journal of Geophysical Research (Planets). 115, 6006. [3] Arvidson, et al., 1992. EOS. 73, 161 - 169. [4] Elston, et al., (2021) Bulletin of the American Astronomical Society. [5] Elston, et al. (2014) IEEE ICRA. [6] Sugimoto, N. et al., 2014 Journal of Geophysical Research: Planets. [7] Peralta, J., et al., 2020. Geophysical Research Letters. 47, e2020GL087221. [8] McGouldrick, K., et al., The Planetary Science Journal. 2, 153. [9] Barstow, J.K. et al., Icarus. 217, 542-560. [10] Cockell, C. S., et al., 2021. Astrobiology. [11] Rimmer, P. B., et al., 2021. arXiv preprint arXiv:2101.08582. [12] Baines, E.K.H, et al., (2021) Astrobiology. [13] VEXAG, Goals, Objective, and Investigations for Venus Exploration. 2019.