PHANTOM: AN AEROBOT MISSION TO THE SKIES OF VENUS.

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Introduction: The selection in 2021 by NASA and ESA of three new Venus missions—VERITAS, DAVINCI, and EnVision—heralded the start of a new era of Venus exploration. But even with these missions, there remains an enormous amount we have yet to learn about Venus—including science questions that require atmospheric data taken at multiple latitudes, longitudes, and altitudes, or measurements taken on or of the surface at individual sites or at larger spatial scales.

In recognition of those 2021 selections, and the remaining science questions best addressed with in situ measurements at Venus, the 2023–2032 Planetary Science and Astrobiology Decadal Survey *Origins, Worlds, and Life* [1] modified the New Frontiers "Venus In Situ Explorer" mission theme to address the following major science objectives:

a) *Characterize past or present large-scale spatial and temporal processes within Venus' atmosphere*;

b) *Investigate past or present surface–atmosphere interactions at Venus*; and

c) *Establish past or present physical and chemical properties of the Venus surface and/or interior*.

The Phantom Mission: Phantom is an ambitious New Frontiers-class (~US$1B) mission concept under development at the Jet Propulsion Laboratory, and features an aerial robot (aerobot) paired with an orbiter to address these and other science objectives from within the Venus clouds (**Figure 1**).

The Phantom aerobot is a variable-altitude balloon and gondola able to traverse an altitude range of 52–62 km with an instrument payload of ~25 kg. Operating in the middle cloud layer and requiring materials and construction methods to resist the high-acidity environment, the aerobot circumnavigates Venus in 5–7 Earth days [2]. To minimize battery power consumption, most science operations will be performed on the day side where solar power is available; the nominal lifetime of the balloon exceeds 30 Earth days.

Supporting the operations of the aerobot is an orbiter that also carries a science payload. The orbiter will assume an inclined, elliptical orbit about Venus to permit synoptic imaging of the Venus atmosphere, serve as a communications relay to Earth, and track the aerobot. The orbiter's lifetime is measured in years, offering continued valuable science at Venus long after the aerobot phase of the mission ends, and operating as a radio relay for subsequent aerial and lander missions.

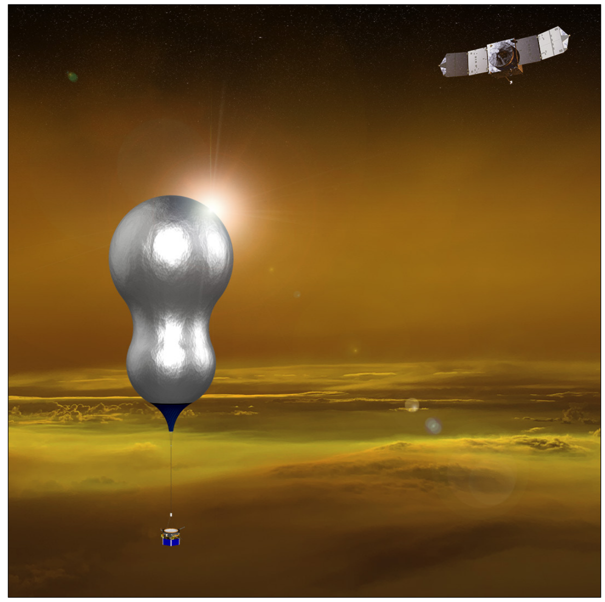

Figure 1. The two elements of the Phantom mission concept. A variable-altitude balloon able to traverse a ~10 km-altitude range carries an instrument-equipped gondola, and is accompanied by an orbiter with its own science payload.

Mission Theme and Science Objectives: Phantom addresses Decadal-level questions by taking as its core science focus the theme of "volatiles."

This theme encompasses (but is not limited to) investigations of the chemical and physical properties and processes of terrestrial planet atmospheres; how terrestrial atmospheres are lost to space; the rates and nature of volatiles released from rocky mantles; the chemical and physical properties with which rocky planets form; the history of volatiles in the geophysical and geochemical evolution of terrestrial planets; and the role of volatiles in developing and maintaining habitable environments.

The Phantom concept is therefore responsive to all three cross-cutting science themes in the 2013–2022 Planetary Science Decadal Survey *Vision and Voyages* [3]—"Building New Worlds," "Planetary Habitats," and "Workings of Solar Systems"—by tackling the following questions:

- *What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres?*;
- *Did Venus host aqueous environments conducive to early life, and is there evidence that life emerged ?*; and

Figure 2. In July 2022, JPL and the Near Space Corporation successfully flight tested a one-third-scale, variable-altitude aerobot prototype. The aerobot ascended more than 1 km above the Black Rock Desert, where pressure and temperature are comparable to the conditions about 55 km above the Venus surface. Credit: Near Space Corporation.

- *Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?*

The 2023–2032 Decadal Survey posed a new set of even more focused cross-cutting questions [1], at least five of which Phantom is particularly able to address:

Q.3 *Origin of Earth and inner Solar System bodies*;

Q.5 *Solid-body interiors and surfaces*;

Q.6 *The atmospheres, magnetospheres, exospheres, and climate evolution of solid bodies*;

Q.10 *Dynamic habitability*; and

Q.12 *Exoplanets*.

To take on this wealth of cross-cutting science investigations, focusing on the "volatiles" theme, the Phantom mission has seven primary science objectives:

1) Establish if the Venus clouds are habitable;
2) Characterize the nature of aerosols there;
3) Determine how volatiles are transported to, in, and through the cloud layer;
4) Ascertain how radiative flux drives convection, circulation, and microphysics in the Venus atmosphere;
5) Search for a modern magnetic field or evidence for an ancient record of intrinsic Venus magnetism;
6) Test whether volcanic eruptions inject volatiles into the atmosphere; and
7) Establish the atmospheric species lost to space.

Technology Development: Although the middle Venus atmosphere is a far more benign environment than the surface, key technical challenges remain. For instance, the Venus clouds are primarily composed of sulfuric acid droplets [e.g., 4], requiring the use of acid-resistant materials on the outer balloon envelope, gondola, and solar panels. Further, the requirement that the aerobot be capable of traversing a range of altitudes has motivated the design of a balloon-within-a-balloon design. The Phantom aerobot therefore features an outer, metallized, unpressurized balloon that is coated in Teflon, which protects against sulfuric acid cloud droplets and sunlight, and which encompasses an inner, super-pressure balloon reinforced with Vectran; exchanging helium between the inner and outer balloons modulates the aerobot's buoyancy and thus altitude [2].

A one-third-scale aerobot prototype successfully demonstrated this design during a set of flight tests in Black Rock Desert, NV in July 2022 (**Figure 2**). These tests validated the use of variable-altitude balloon technology in temperature–pressure conditions similar to those the full-scale aerobot would encounter in the middle Venus atmosphere, and provided crucial flight data for simulation models of full-scale aerobot operations at Venus. Work continues to develop ever-higher-fidelity balloons with materials and seams able to withstand the temperatures, pressure loads, sulfuric-acid concentrations, and solar radiative heating conditions that characterize the Venus clouds.

Outlook: With coupled aerobot and orbiter flight elements, the Phantom mission addresses Decadal-level planetary science questions in a way not possible from orbit or via a single descent profile [1]. Although balloons have investigated the Venus atmosphere before [5], the long-duration, globe-encircling capability of the Phantom aerobot represent a paradigm shift in how we can explore Venus. And, because the second planet sits at the intersection of key questions [1] of planetary formation, atmosphere gain and loss, dynamic habitability, and the evolution and fate of Earth-size worlds [6], Phantom enables the planetary, exoplanetary, and heliophysics communities to take the next giant leap in our understanding of the Solar System—and beyond.

References: [1] *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* (2022) Nat. Acad. Press. [2] Izraelevitz, J. S., et al. (2023) *LPS*, *54*, Abstract 2279, *this mtg*. [3] *Vision and Voyages for Planetary Science in the Decade 2013–2022* (2011). Nat. Acad. Press. [4] Kawabata, K., et al. (1980) *JGR*, *85*, 8,129–8,140. [5] Sagdeev, R. Z., et al. (1986) *Science*, *231*, 1,411–1,414. [6] Kane, S. R., et al. (2019) *JGR*, *124*, 2,015–2,028.