WHY WE NEED A LONG-TERM SUSTAINABLE VENUS PROGRAM.

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Introduction: Early in the space program, Venus was recognized as a critically important target for exploration by both the U.S. and the Soviet Union. A series of orbital (*Pioneer Venus* (USA), *Venera* (USSR)) and landed missions (*Venera, Vega* (both USSR)) returned landmark data on geochemistry, general rock type, surface geology, and about the atmosphere. The NASA/JPL *Magellan* orbiter mission, concluded in 1994, was groundbreaking in its many advances, studying gravity, topography, and surface characteristics via moderate-resolution synthetic aperture radar (SAR) and altimetry. Since then, Venus has only been studied from orbit by the ESA *Venus Express* and JAXA *Akatsuki* missions; those missions, although not *focused* on the Venus surface and interior, have provided substantial new insights into atmospheric composition and dynamics, as well as tantalizing hints at variations in the regional surface composition of arguably the most-Earthlike body in our Solar System. At the same time, all these missions have raised at least as many questions as they answered—while exploration of other Solar System bodies has proceeded rapidly, leaving the integrated state of knowledge of Venus dependent mostly on decades-old data and models.

Over the last 3 decades, our knowledge gap relative to other terrestrial planets has become enormous. Venus is one of the few bodies in our Solar System with an atmosphere and active, internally-driven geologic processes. Thus, no single mission can fully tackle the fundamental issues of Venus' evolution. Therefore, we make the case for a sustained *program* of coordinated Venus exploration designed to address the many compelling unanswered science questions.

New Motivation for Venus Science: Several compelling recent advances have made the need for a coordinated Venus program especially timely for the 2020s:

1. The realization that there are thousands of Venus-like exoplanets and that in fact there might be more Venus-like than Earth-like exoplanets [1–5].

2. New models suggest that Venus may have had oceans of liquid water for as long as ~3 Ga, an order of magnitude longer than Mars and potentially longer than Earth [5–7], raising issues of past habitability.

3. Venus Express inferred regional-scale evidence of fresh, un-weathered basalt (via IR emissivity modelling at 100 km scales) accompanied by intermittent increases in SO_2 concentration likely arising from volcanic outgassing. These results raise the tantalizing prospect that Venus is still volcanically active [8–11].

These and many other compelling discoveries make the case for a comprehensive, multi-disciplinary coordinated Venus program urgent and compelling. Advances in instrumentation and spacecraft components allow for novel and new ways to explore Venus both from orbit and from within the atmosphere, as well as on the surface. Global compositional mapping of the surface, precise measurements of the isotopic ratios of noble gases, and long-lived stations are now in the realm of the possible. Many of these advances are reflected in the updated Goals, Objectives, and Investigations document [12] recently completed by the Venus Exploration Analysis Group.

The need for continuous exploration of Venus: Our view of Mars has fundamentally changed since *Mariner 9* and *Viking* thanks to an extensive and *continuously adapting* Mars exploration program—which was purposefully developed as a science-guided program [13–15]. Each new instrument has provided new details and insights, including definitive geodetic topography (MOLA), expanding our understanding of the planet and paving the way for landers, rovers, and ultimately sample return. A coordinated Venus exploration program has the potential to transform our view of our closest sibling in the Solar System in a similar way, but with different (yet critical) emphases. Venus is a laboratory for understanding the fates that await Earth-size (where Earth-size = Venus-size) rocky planets. It can inform us what potentially might happen to a once-blue-and-green planet. [6, 7, 16].

For Venus missions, SAR systems are the equivalent of cameras; each unique radar system can provide a different element of understanding the surface and interior, including geodetic topography and hyperresolution imaging, both of which have proven essential for Mars. Combined with spectrometers to study the deep atmosphere and surface and in situ atmospheric composition, such data would pave the way for advanced aerial platforms, chemistry probes, landers, and, ultimately, mobile surface exploration elements. A long-lived geophysical lander on Venus would be transformative for Venus science. Indeed, Apollo landings provided the fundamental view of magma oceans on terrestrial planets, and the *Mars InSight* lander is now offering us an unprecedented view of geological activity on Mars, making the case for similar measurements at Venus.

What are the elements of a coordinated Venus program? Given our evolving knowledge of exoplanets [2] and continued technological developments [17], there is an urgent need for comprehensive study of all aspects of Venus science, performed by a set of complementary and coordinated missions including, but not limited to:

Venus Orbiters: The study of the surface by radar imaging and geodetic topography; SAR interferometry to search for active deformation; surface composition; searching for and monitoring volcanic activity over long durations; model-based mineralogy at broad scales (> 50 kilometers); and monitoring of the atmospheric dynamics and chemistry and escape processes.

Venus Atmospheric Sampler Probes/Aerial Platforms: In situ analysis of stable and noble gas abundances and isotopes; measurements of trace volatile abundances (H_2O, SO_2, OCS, CO), including below 40 km at high vertical sampling, where very little is known; assessing the transition into the super-critical CO_2 domain, and with IR-based descent imaging to complement orbital SAR and spectroscopy.

Venus Landers: Chemistry, mineralogy, rock type, oxidation state, texture, and effects of weathering/atmospheric interactions in both the volcanic plains and tessera regions, with multi-scale imaging at the surface and on descent; search for seismic activity with long-lived surface elements.

We need a Venus program and we need it now: All these basic mission types are already feasible with existing technology [18–25]. However, continued investment must occur for advancing longer-lived power, telecommunication elements as well as electronics and instruments that can operate at the Venus surface temperatures. Balloons and their payloads as well as chemistry probes have no current investment and that should be part of any over-arching Venus program. An analogous technology program was established for Mars since 2000 and this is what enabled continuously advancing observations of that planet from orbiters and rovers.

Each element on its own will provide key insights—but the *synergy* of a coordinated Venus program has the potential to boldly transform our understanding of rocky planet evolution and that of large-atmosphere exoplanets. This latter aspect will become ever more important as we enter an era of transiting-exoplanet spectroscopy thanks to JWST, WFIRST [26, 27]. Without a sustainable program of science-guided Venus exploration, we risk failing to understand key aspects of planetary and Solar System evolution, and will not be best positioned to grasp the significance of Earth- and Venus-like exoplanets as they are discovered (with TESS and CHEOPS [28, 29] now, and soon with JWST [2,27]).

The genesis of a coordinated Venus program could begin with the selection of Venus missions funded under the NASA *Discovery* and ESA M5 *Explorer* programs, which have elements addressing many of the required measurements and science described above. But as we have learned from exploring Mars and the Moon, if we are to fully understand Venus we must start to think of an evolving symphony of missions over the coming decades.

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