VEXAG | A Strategy for Venus Exploration

A White Paper

Draft for Community Input

Preamble

The 2023–2032 Planetary Science and Astrobiology Decadal Survey *Origins, Worlds, and Life* recommended that "NASA should develop scientific exploration strategies, as it has for Mars, in areas of broad scientific importance, e.g., Venus…, that have an increasing number of U.S. missions and international collaboration opportunities" (*OWL*, p. 22-10).

In NASA's initial responses to that Decadal Survey, the agency asserted that "…specific scientific exploration strategies should be community generated by bodies such as the Analysis Groups," thus placing the onus on community-led and -supported exploration strategies.

As a result, in late 2022 the Venus Exploration Analysis Group began a year-long effort to develop a new exploration strategy for Venus, reflecting both the 2021 selections of the VERITAS, DAVINCI, and EnVision missions and the sweeping comparative planetology recommendations relevant to Venus in *Origins, Worlds, and Life*.

This is that strategy.

Taking a broad look at the scientific, technological, and programmatic advances required to address the key outstanding questions that Venus poses, this document outlines a set of actions available to NASA, VEXAG, and the planetary science community at large to establish a sustained program of Venus exploration in the years and decades ahead. Key to this approach is recognizing Venus not only as a worthy target of exploration in its own right, but as a unique setting where multiple, cross-disciplinary, Decadal-level planetary, Earth, and heliophysics science questions can be addressed.

Through findings and recommendations for multiple stakeholders, this exploration strategy document will help lay the foundation for the establishment by NASA of a formal Venus Exploration Program in the 2030s.

Venus as a Science Nexus

Venus sits at the center of some of the most important planetary science questions we have, many of which were identified and prioritized within the last ten years. In *Origins, Worlds, and Life*, Venus as a scientific target features 261 times in the main text, and is included in 46 Strategic Research areas in seven of the 12 priority science questions—spanning the evolution of the protoplanetary disk; the origin of the inner Solar System worlds; the link between solid-body interiors and surfaces; the properties of solid-body atmospheres, exospheres, and magnetospheres; the prospect for a catastrophic loss of habitability in Venus' past because of climate change run amok; and what Venus can tell us of large, rocky worlds generally. Indeed, VERITAS, DAVINCI, and EnVision all advertised their multi-thematic relevance to a future in which Venus is a critical science destination.

It should be no surprise that we have so many unanswered questions about Venus for, despite being the target of a great many missions in the 1960s and 1970s, we know remarkably little about this Earth-size world today compared with the rest of the inner Solar System. Radar data from the Magellan orbiter mission (1990–1994) show a wealth of tectonic and volcanic landforms on Venus but, unlike for Earth, no evidence of a global plate tectonic system. Those radar images do reveal numerous high-standing, heavily deformed regions called tesserae, which are tempting to compare to Earth's continents. But we have no reliable geochemical nor mineralogical data with which to determine what these regions (nor any others) are dominantly made of, and thus how they were formed. Although tantalizing clues about tesserae have been gleaned from more recent orbital missions including Venus Express and Akatsuki, these elevated terrains—occupying around 7% of Venus by area—remain enigmatic but critical to understanding Venus' evolutionary history.

Indeed, we lack important chemical data for the planet's interior, leaving as a mystery the materials from which Venus accreted, how and how much water was delivered during its development, and what minerals and rocks make up its crust and mantle. No mission to Venus so far has detected an internally generated magnetic field, nor evidence for remanent magnetism in its crust, and we have precious little information about the size or state of the planet's core. The water budget of Venus' interior is also unknown, even though measurements of the atmosphere and the results of tectonic models have been generally interpreted to mean a dry interior for Venus.

The Venus atmosphere is a dense, CO_2-dominated greenhouse that renders the surface hotter than a self-cleaning oven and under a pressure equivalent to an underwater depth of ~900 m on Earth. The atmosphere revolves around the planet's axis up to 60 times faster than the solid body, but the reason for these vastly disparate rotation rates is unknown. There are numerous reactive trace gases present, likely many undetected especially below 20 km altitude, but we do not know when or how this atmosphere and current climate developed—is it a relict primordial atmosphere, or was Venus once far more clement and perhaps even Earth-*like*? If not, why not? If so, when and why did Venus' climate diverge so drastically from that of Earth?

Origins, Worlds, and Life emphasized that Venus is a valuable science target in no small part because, as a large rocky planet with a massive atmosphere, it holds the key to understanding how and why plate tectonics, intrinsic magnetic dynamos, surface liquid water, and habitable conditions can emerge on such worlds—or how and why *not*. This understanding is crucial if we are to establish why our own planet has remained habitable almost since its formation. Because Venus is closer to the Sun than Earth or Mars, the chemistry of its interior, surface, and atmosphere holds important constraints for questions of cosmochemistry, planetary nebula processes, and the evolution of the Solar System itself. Further, Venus serves as a cautionary tale when interpreting the limited information we have for large rocky exoplanets: at present, we can only tell if a terrestrial exoplanet is Earth-sized, not Earth-like, and a promising exo-Earth candidate could well turn out to be an exo-Venus. Determining why Earth and Venus differ so much today will be powerfully enabling of our efforts to distinguish Earth- from Venus-like worlds around other stars, and their divergent evolutionary histories.

As for every other Solar System destination, Venus' mysteries will be unveiled with robotic spacecraft exploration. The 2021 selections of the VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) and EnVision orbiters, and the DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging) flyby/descent probe, will begin to revolutionize our understanding of Venus just as Mars Global Surveyor and Mars Reconnaissance Orbiter did for the Red Planet in the 2000s. Yet these new Venus missions will leave unaddressed myriad major questions—emphasizing the point that no one (or three) missions can resolve every facet of Venus science, nor respond to the findings of the others as a new mosaic of Venus emerges.

For the atmosphere, we must go beyond a single vertical profile, to understand its three-dimensional, time-variable cycles and dependencies. For the surface, we need to truly determine the nature, composition, state of weathering, and evolution of surface and near surface materials, from the lowest-lying volcanic plains to above the emissivity "snow line" in the high-standing tesserae regions. For the interior, we must establish the size, state, and composition of the core, and the structure of the mantle. We need to learn just how alive Venus is, volcanically and tectonically, plumbing the subsurface and understanding its mantle and core.

Many of these major questions require in situ platforms with modern analytical instrumentation, as only the DAVINCI descent probe will carry in 2031. Balloon-based aerobots can characterize the atmosphere's chemical and physical properties over much longer time scales than even the most advanced descent probes, and are ideal platforms for searching for evidence of ancient and modern magnetic fields and sources of seismicity. Lander missions can provide much better rock chemistry and definitive mineralogy than their precursors could, and networked landers equipped with high-temperature electronics can return unprecedented, long-term science measurements such as seismicity. Much orbital-based remote-sensing science remains, too, including efforts to understand atmospheric superrotation and atmosphere–space environment interactions. And, although requiring of technical capabilities that are clearly in the future, the scientific rationale for roving on and even returning samples from Venus is every bit as applicable and compelling as it is for the Moon and Mars—and perhaps more so, given the seeming scarcity of Venus meteorites in the world's collections. Indeed, whether we can understand if some exotic meteorites here on Earth are from Venus may well require in situ analytical measurements that have yet to be made.

Finding: As for the Moon and especially for Mars since 2000, an openly planned, integrated, and diverse set of mission platforms and measurement approaches are key to exploring the most critical facets of Venus as a system, which in turn will offer new discoveries relevant to a much broader range of key planetary science issues.

Path Forward: **NASA could consider how to implement a sustained, integrated program of technology development and spacecraft exploration of Venus to fully leverage the lessons this planetary science nexus offers.**

Exploration-Enabling Technologies and Infrastructure

Venus provides in a single world one of the most diverse, technically challenging combinations of environments available: an orbital domain that permits the use of orbiting platforms with well-suited instrumentation but challenged by a thick, opaque atmosphere; a middle atmosphere with the most Earth-like environmental conditions in the Solar System but with high variability across altitudes; and an extreme, high-pressure high-temperature setting at the surface that strains existing technical capabilities. The exploration of Venus thus requires an integrated approach that couples technology development with driving science questions and adapted measurement approaches, and vice versa.

The science questions that require long-term landed science measurements are among the most pressing for Venus—but they require the greatest technological investment. On the other hand, the technologies needed for short-lived landers and aerial platforms are generally more mature, enabling compelling science at a lower risk and cost threshold.

Short-term landers are able to provide measurements of rock chemistry, mineralogy, multispectral imagery, and even near-surface atmospheric measurements and surface–atmosphere chemical and physical interactions. Modern short-duration landed platforms can carry mineralogical and petrological assessment instruments that would provide a multi-generational advancement beyond the Venera-era landers of the 1970s and 1980s. Moreover, contemporary short-term lander designs enable lifetimes of up to eight hours of surface operations, thus allowing far greater precision (and more measurements) than those twentieth-century missions.

Variable-altitude, balloon-borne aerial robots with modern instruments will allow unprecedented exploration of the middle Venus atmosphere. By changing altitude, such aerobots can take advantage of prevailing winds at different altitudes, providing some amount of directional control as the platform moves with the zonally super-rotating atmosphere. From within the atmosphere, investigations into cloud habitability, atmospheric chemical and physical cycles, geophysics, and even surface imaging from below the cloud base become possible. Key to this type of platform are advances in autonomous guidance, navigation, and control, as well as atmospheric entry systems and balloon deployment and inflation mechanisms.

The advent of long-duration, high-temperature systems will be *game changing* for Venus. Extended-life landers could provide the first true measurements of temporal phenomena at the surface such as levels of seismic activity, long-term surface weather conditions across diurnal cycles, and chemical monitoring of the atmosphere and its interactions with surface materials. Advances so far in high-temperature technologies to enable a spacecraft to operate for months at the Venus surface are promising: high-temperature sensors, communication, power storage, and other subsystems are in limited (by investment) states of development, and in some cases nearing mission viability as technology demonstrators. Continued development of high-temperature technologies, including memory, power, actuation, communication, and imaging, is crucial for a sustainable Venus exploration program. Although systems-level long-duration surface operations at Venus are yet some way off, a high-temperature, long-duration landed technology demonstration mission in the near-term would represent a major step forward in the maturing of this technology, either as a standalone mission or as a SIMPLEx-supported secondary payload.

Whether targeting the rolling plains or the tesserae, terrain-relative navigation and hazard avoidance technologies that have been applied so successfully to Mars would shrink landing ellipse sizes and thus enable the precision targeting of high-value science landing sites. Characterization of the Venus surface at lander scales (e.g., with DAVINCI descent images, dedicated imaging dropsondes, high-resolution radar imaging from orbit), especially for the tesserae, could usefully inform the safe landing requirements for future landers. Ultimately, surface mobility will be key—for sampling multiple sites on the Venus surface with a comprehensive instrument suite will enable the kind of remarkable science now being performed at Mars by flagship-class analytical chemistry rovers.

Indeed, an indispensable facilitator of complex surface operations, including by the Mars Curiosity and Perseverance rovers, is the satellite-based communications “proximity-relay” infrastructure at Mars. The Mars Relay Network comprises both NASA and ESA orbital assets, and as such is also a valuable example of international cooperation in planetary exploration. At Venus, an orbital communications infrastructure would aid aerial platform tracking and provide aerobots and landed assets—whether short- or long-duration in nature—with continuous data reception, substantially enhancing the science return of any in situ investigation. Importantly, its close proximity to Earth means that Venus is an oft-used body for gravity assists, thus offering more opportunities for secondary payloads than Mars or any other destination. And, by utilizing SmallSat or even advanced CubeSat technologies, such relay satellites can likely be implemented at a relatively low cost. Innovations in SmallSat capabilities at Venus could also demonstrate independent science investigations such as meter-resolution side-looking radar imaging as well, bridging the current gap between Magellan and upcoming orbital SAR instruments and sub-cloud descent imaging, as planned for the DAVINCI mission.

Along with developing spacecraft component technologies, honing instrumentation and sample handling for Venus-specific use will lead to improvements in all exploration modalities. For example, reducing the size and power requirements, yet increasing the speed and precision, of both stand-off and direct-sample landed instruments that have been used previously on Mars will lead to improvements in Venus lander capabilities. Such improvements are needed to characterize the major, trace, and isotopic elemental abundances and bulk mineralogical, petrological, and petrographic properties of Venus surface materials sufficient to resolve the key geochemical questions we face, as these instruments require environmental protection and do not yet have realistic high-temperature operational capabilities. (Between 1982 and 1985, the Soviet Venera 13 and 14 and VeGa 1 and 2 landers successfully carried out in situ XRFS measurements, but were necessarily restricted to hour-long surface operations.) A hybrid architecture could take advantage of increasing number of high-temperature analytics that can provide valuable, narrowly-scoped, unique, and/or complimentary data to the more conventional instruments, enabling a new generation of short-lived lander missions with dramatically increased science impact than 1970s and 1980s-era missions. Aerobot-borne analytical instruments will similarly benefit from advances in sample handling, throughput, and measurement precision, as well as from high-temperature technologies. For example, the ability of an aerial platform to operate below the cloud deck, where temperatures readily exceed 100°C and approach 400°C or more within a few kilometers of the surface, will enable investigations so far possible only for Earth, Mars, and Titan.

The development of electronics, instruments, and spacecraft subsystems for the Venus clouds, lower atmosphere, or surface requires a robust set of environmental facilities in which they can be tested, validated, and optimized. Such facilities also provide unique opportunities for collateral benefits to science, from investigating how surface materials physically and chemically weather under extreme temperatures and pressures to testing different candidate aerosol species that may be present in the cloud layers. Several laboratory capabilities already exist for simulating Venus-relevant conditions, including the Glenn Extreme Environments Rig and the JPL-Caltech Venus Cloud Simulator Facility, which can replicate conditions at the surface and the processes that form and sustain the planet's sulfuric acid clouds, respectively. But the questions we have in hand, the upcoming Venus missions—VERITAS, DAVINCI, EnVision, and missions by India, Japan, China, and others—and the future discoveries that await us all require that such laboratory and experimental capabilities in the United States must be not only maintained but expanded upon. New investments in Venus test chambers in the U.S. for DAVINCI and in Europe for Venus exploration generally could be catalysts for widely available Venus environment facilities and enablers of future missions to the planet.

There is a yet more pressing need, affecting not only Venus exploration but planetary investigations generally: the path from component and subsystem technology to a fully integrated, flight-ready system. Traditionally, NASA technology development is carried out at the component or instrument level, with limited opportunity for integration and testing of subsystems unless in the context of an already-selected mission or of a flagship under implementation. The result is that new paradigms for mission implementation are not likely to be selected unless risk (real and perceived) is reduced, but there is no viable route for demonstrating those new implementations as integrated systems to reduce such risk. Venus lander and aerial platform concepts will benefit hugely from an approach that integrates component and subsystem technology to demonstrate basic systems-level viability and appropriate refinement and optimization, as was accomplished for the Mars Exploration Program with efforts such the as Mars Instrument Design and Development Program in the 2000s.

Finding: Long-duration, in situ platforms in the clouds and on the surface, enabled by maturing technologies, represent the next logical step in developing a transformational understanding of the Venus atmosphere and surface.

Finding: An orbital communications infrastructure at Venus will be a force multiplier for enabling planned and future Venus exploration; there may be an opportunity to sustain one or more of VERITAS, DAVINCI, and EnVision in Venus orbit for relay going forward.

Finding: Field experiments, laboratory facilities, and instrument development supporting both technology and science objectives are critical to the success of future Venus missions and together represent an important element of Venus exploration infrastructure at a "program" level.

Path Forward: **NASA could take a new approach to Venus exploration by identifying essential technologies required to address key Decadal-level science questions and supporting the development of those technologies from the component to the systems level.**

Supporting Venus Science in the United States

The VERITAS, DAVINCI, and EnVision missions will herald the upcoming era of Venus exploration referred to as the "Decade of Venus." But the realities of mission budgets, formulation, and implementation mean that even the most imminent of these will not launch until the late 2020s, and the major science payoffs are eight or more years away as of this writing—such that we've embarked upon the "*Decades* of Venus." The reality is that these missions' discoveries will not begin impacting the trajectory of planetary science until the mid-2030s.

Yet that timing affords us the opportunity now to increase our engagement with Venus science, maximizing the return on these upcoming missions and the new discoveries they will surely raise, and laying the groundwork for addressing the next set of major questions we must tackle. The recently constituted Venus Science Coordination group ("VeSCoor") is one such example of the efforts we can make going forward. Equally, continued laboratory simulations of the planet's atmosphere and surface processes, the development of new and better models of Venus' climate and interior, and sustained analysis of existing Venus data sets—from surface investigations with Magellan data to interactions between the upper atmosphere and the space environment with Pioneer Venus and Venus Express measurements—will together best position us to take advantage of the upcoming Venus missions, and set the stage for more to follow.

Much Venus research in the U.S. is funded by NASA research and analysis (R&A) programs. Recent changes to those R&A programs have been more encouraging for Venus science, such as the inclusion of Magellan synthetic-aperture radar (SAR) mission data into the Discovery Data Analysis Program, and the recognition of quadrangle geological maps as part of the Planetary Data Archiving, Restoration, and Tools program. Yet there is more NASA can do to support and grow the U.S.-based Venus science community.

For instance, there is a compelling need to finish the remaining Magellan quadrangle maps ahead of the VERITAS and EnVision missions, to enable comparisons with geological maps prepared with those future, high-resolution radar imaging and topographic datasets and to help guide selections of EnVision regions of interest; such mapping could be an explicit part of the annual PDART solicitation. Supporting the utilization and maintenance of existing Venus experimental facilities, and standing up new such community infrastructure as needed, is vital if we are to fully understand atmospheric and surface chemical and physical processes at Venus-relevant temperatures and pressures. And enabling more community meetings in which scientists who study planetary processes relevant to both Venus and to other worlds can meet and learn from each other—such as the LPI-led Venus

Initiative or the joint VEXAG/OPAG/ExoPAG/MEPAG/MexAG "Exoplanets in Our Backyard" workshop series—will be hugely effective in demonstrating the value of Venus as a key science nexus to the broader planetary community. A catalytic "Venus Fundamental Research" initiative could help promote and apply advances in the science that will come from the missions to be launched between 2029 and 2033, an approach that was successful in the early years of the new Mars Exploration Program.

Science and technology create a mutually beneficial cycle: new science questions drive new technologies to answer them, and new technologies in turn motivate new science questions. The advancement of NASA's technology-focused R&A programs would thus effectively enable future Venus science through a third HOTTech solicitation, to help bring high-temperature technologies to systems and applications levels of readiness. And establishing a new "CloudTech" program, focused on technology development for the upper, middle, and lower atmosphere of Venus—which would be applicable to other worlds with atmospheres—would powerfully address the needs of the next-generation in situ Venus missions. For example, thus far there have been no investments associated with operating instruments in a super-critical fluid atmosphere relevant to Venus surface conditions.

Finding: The timing of the next crop of Venus missions offers a unique opportunity now to ready the planetary community for the new science yet to come, by sustaining and enhancing R&A science and technology programs and community workshops.

Finding: Many of the highest technology needs (e.g., aerial platforms, high-temperature systems, new analytical chemistry instruments, navigation lidar) for next-level Venus science are also technology needs for multiple other planetary targets and target environments.

Path Forward: **NASA could place a greater emphasis on Venus-focused science and related technology in its R&A and meetings portfolios to take advantage of the planet's unique combination of processes and phenomena that are relevant to numerous other Solar System and extrasolar bodies.**

Building Venus Exploration Partnerships

As a unique planetary science nexus, Venus offers considerable value to researchers beyond those studying the planet's interior, surface, and atmosphere. Venus holds lessons for those investigating topics as diverse as planetary habitability, cosmochemistry, aeronomy, the space environment, heliophysics, exoplanets, and even some creative aspects of human exploration. What is vital, however, is that other disciplines and the Venus community are able to recognize the value that each offers the other. Thus, by partnering with as broad a cohort of stakeholders as possible, the cause of Venus exploration will be strengthened.

For example, the Mars Express and MAVEN missions have enabled the growth of a large and active Mars upper-atmosphere community, which now realizes that a full understanding of the dynamics and evolution of the planet as a whole requires comprehensively characterizing the transport of materials through that atmosphere. To what extent do lower-atmosphere processes such as dust storms or volcanic activity affect the atmosphere? What roles do the solar cycle and space weather play?

With the upper-atmosphere and space environment insights we have for Earth, Venus offers a crucial third piece of this comparative planetary puzzle. Although Pioneer Venus Orbiter and Venus Express made great strides in some aspects of understanding the planet's atmospheric dynamics, they were not designed to investigate these processes as comprehensively as has been done at Mars, nor with the overall goal of understanding planet evolution. A Venus mission with a focus on upper-atmosphere–space environment interactions will therefore be of major interest to the planetary atmospheres community generally, encompassing those scientists who have yet to focus on Venus.

The heliophysics community has a vested interest in long-term monitoring of the Sun, but currently lacks any such capability at Venus. A mission to the second planet capable of remote sensing of the Sun or of in situ measurements of the solar wind will, in addition to Venus science, enable studies of stellar processes and solar wind evolution through the Solar System, as well as offering a valuable solar monitoring capability.

Venus' tectonic and volcanic characteristics and evolution could provide clues to those Earth scientists studying the geochemical, geophysical, and geodynamic properties of the Archean, the geological record of which is now largely lost to us through subduction and erosion. For example, the planet's enigmatic coronae show features that resemble small-scale convergent tectonic plate boundaries on Earth. Venus' ancient terrains, the tesserae, have long been regarded as potential counterparts to the continents on Earth, perhaps even dating to a time of sustained habitable conditions at the surface that included liquid-water oceans. The sedimentary cycle on Venus remains poorly understood, but may offer clues to how environments changed over time, and even from a habitable period to that of today. Missions that offer new insights into topics as diverse as corona formation, tessera composition, history, and driving geodynamic regime, and sedimentary processes will impact not only how we interpret Venus' geological and climate evolution, but our understanding of the early processes that shaped our own world.

The field of extrasolar planets is flourishing, with more than 5,500 confirmed exoplanets found so far. A major focus of exoplanet research is the search for Earth-*like* planets, thought to be a subset of so-called "eta-Earths"—those Earth-size or larger rocky worlds within a star's optimistic habitable zone. Yet vital to this search is an understanding of the likely occurrence rates of "eta-Venus" worlds, and whether such worlds might be the more common type to develop, which requires establishing why the climate histories of Earth and Venus have so drastically diverged. It stands to reason, then, that engaging with the exoplanetary science community is an obvious and important step in advancing the study of Venus—and vice versa.

Venus could also serve as an important stepping stone for *human* exploration of the Solar System. Venus can be—arguably should be—how we get to and/or back from Mars. Crewed flybys of Venus on the outbound or return leg to minimize delta-*V* (and entry velocities for crewed spacecraft) and mission duration are valuable precursor missions for the current best architectures of human spaceflight to Mars. These flybys further offer abort-and-return-to-Earth options as well as opportunistic science during closest flyby approach. Incorporating Venus flybys in crewed Mars missions turns human exploration of one destination into human exploration of the Solar System, changing our aspirations from simply boots in the red dust to a much grander endeavor, and, uniquely, de-risking human spaceflight to Mars and offering a testbed for human exploration technologies.

Even though the last NASA-funded mission to Venus ended in 1994, there has been an explosion of scientific enlightenment and understanding about Venus' geology, atmosphere, and climate evolution in recent years—only enhanced by the 2021 mission selections. Numerous syntheses of Magellan and Arecibo findings were published in the years since that mission, and more have been prepared ahead of VERITAS, DAVINCI, and EnVision. These books and review papers are valuable resources, especially those building on post-Magellan topics relevant to Venus including rocky exoplanets, new climate evolution and interior dynamics modeling, and the finding of strong evidence for ongoing volcanism on the planet. But such volumes would be effectively complemented by a new, comprehensive review article published in a journal with a reach that encompasses planetary geoscientists, atmospheric scientists, astronomers, Earth scientists, and other constituencies with an interest in exploring Venus. This review article would summarize in shorter form than a book the current state of knowledge of Venus science, outline the opportunities and challenges that lie ahead, and serve as a call to arms for garnering support for continued Venus exploration from across the planetary science spectrum.

Origins, Worlds, and Life placed a great emphasis on process, not planet—and Venus is that rare Solar System body where questions that transcend and cross-cut multiple distinct disciplines can be answered, and fed forward across the driving themes in NASA's science portfolio. Forging new and developing existing relationships with, for example, the planetary atmospheres, heliophysics, Earth science, exoplanetary, and human exploration communities through research collaborations, conference sessions, workshops, special journal issues, etc. will only serve to drive more demand and support for Venus exploration.

Finding: The exploration of Venus offers substantial value to the wider planetary and Earth science communities, and there is major scope to develop and grow new, mutually beneficial partnerships with diverse scientific disciplines.

Path Forward: **The Venus community should actively engage with as broad a cohort of scientific disciplines with a shared interest in exploring Venus as possible, to market the message that "Venus science *is* planetary science writ large," and to identify how resources can be pooled together to do compelling, impactful science of interest to multiple communities.**

Venus Mission-related Actions

In preparation for *Origins, Worlds, and Life*, a mission concept study for a Venus Flagship Mission (VFM) was carried out in 2020 as part of NASA's Planetary Mission Concept Studies call. Because this ambitious concept predated the 2021 selections of VERITAS, DAVINCI, and EnVision, it addressed a broad range of science goals that, in part, happened to overlap with those missions. Moreover, the VFM concept included a lander that would target a narrow landing ellipse in the tesserae, necessitating considerable autonomy and flight-control technology development. Ultimately, the independent cost estimate for VFM as studied was sufficiently great so as to result it being ranked lower in priority than other, competing flagship-class concepts.

Nonetheless, *Origins, Worlds, and Life* found that a landed flagship mission to the plains could achieve science of similar impact to the 2020 VFM concept, and that an independently costed flagship-class Venus lander mission to the plains would be a valuable basis from which to advocate for prioritizing a Venus flagship in the next decadal survey. A plains-targeted flagship would advance key outstanding science questions we have for Venus without obviating the need for (and perhaps even encouraging) later landed missions to the tesserae, but would not incur the high technical and feasibility costs associated with autonomous flight control given the near-term state of technology, and can be safely designed with existing Magellan data.

Indeed, a flagship-class tessera lander would be enabled by the high-resolution radar image and topography data VERITAS and EnVision will return in the 2030s, and by the subcloud image and topographic data DAVINCI will return of Alpha Regio during its descent to that tessera exposure—although Category 1, fully-selectable Venus lander missions targeting both the plains and tesserae have been proposed to the New Frontiers competition in the past (e.g., 2017's Venus In situ Composition Investigations concept), demonstrating the viability of at least mid-size missions even without new data.

NASA's New Frontiers competition has, since its inception, featured a "Venus In Situ Explorer" (VISE) mission theme, focused on addressing science questions from within the atmosphere or on the surface. There have been multiple proposals to that theme in consecutive NF competitions and, although several were deemed fully selectable, none has so far been successful. In the run-up to the NF5 competition in 2022, NASA deleted the VISE theme from the list of permitted mission themes despite there being no suggestion from the community nor any advisory group to do so. The next NF competition has been delayed several years, and there is no information yet as to what mission themes will be included in that call. But progress on the *next* generation of Venus mission concepts was set back by this deletion, even if it proves to be temporary. Thus it is vital to the sustained exploration of Venus that NASA allows mission proposals to the second planet to be submitted to future New Frontiers competitions, especially given the revised “VISE” theme in *Origins, Worlds, and Life*.

Finding: Efforts to prepare both for the data return from the VERITAS, DAVINCI, and EnVision missions and for the next generation of Venus missions will be most effective with NASA and the Venus community acting collaboratively and in concert, as exemplified by the VeSCoor activity.

Finding: Continued Venus exploration will be severely hampered if NASA deviates from the recommendation of the Decadal Survey to retain the “VISE” theme in the New Frontiers AO competition, unless advocated for by the Venus community or advised to do so by an appropriately constituted independent group.

Path Forward: **NASA and the Venus community could coordinate efforts to study a new flagship mission to the rolling plains as part of a broader program of Venus exploration, to establish the cost and technical feasibility of such a mission as a precursor to later, more ambitious landers to the tesserae.**

The Long-Term Vision for Venus

Venus has long been a compelling exploration target—and the 2021 selections of VERITAS, DAVINCI, and EnVision cemented that status. Since then, the Venus community has markedly increased in size, and we can only expect interest in the second planet to grow.

Data from those new missions won't begin to arrive until the early 2030s, but there are ample actions NASA and the Venus community can take now to both prepare for the new discoveries to come, and to be optimally positioned for the *next* set of missions to Venus. Strengthening the Venus community in the United States and internationally, including with new collaborations that reflect the diversity of the geo, planetary, and space sciences—astrobiology, exoplanets, heliophysics, and so on—will help establish Venus as a crucial destination to address major, Decadal-level NASA science objectives. By demonstrating the value proposition of Venus to planetary scientists, engineers, NASA, and other stakeholders including Congress, Venus researchers will be able to create even more interest in and support for a sustained, strategic program of Venus exploration.

Importantly, previous successful exploration efforts have hinged on a clear, concise message—think "follow the water" for Mars. Establishing in short order the unique selling point of Venus, distilling it to a succinct statement, and strategizing how to advertise that statement to relevant audiences could be key to bringing together the disparate stakeholders needed to support a Venus Exploration Program.

The road to a sustainable and funded VEP at NASA will be a long one, given the magnitude of such an undertaking and the fact that NASA's Planetary Science Division at present only has two dedicated Programs, one each for the Moon and Mars. But whereas the first (and, likely some day, the second) of those bodies has an active human exploration focus, Venus is not a destination for in situ crewed missions—at least not in this century.

What Venus *does* offer is an unrivalled, nearby, and readily accessible destination for answering some of the most pressing planetary science questions we can ask. And the timeliness of Venus missions with on-target science in six to twelve months after launch makes it a quick return-on-investment destination that crosses science community boundaries, especially when compared with the necessarily long cruise phases of missions to the outer planets and Mercury.

The 2033–2042 Planetary Science Decadal Survey is a natural vehicle through which a community-supported recommendation that NASA establish a Venus Exploration Program can be made. The next survey membership will presumably be constituted in the late 2020s—around the same time frame as the Decades of Venus will truly begin. Interpreting the findings of VERITAS, DAVINCI, and EnVision within the context of a larger, coordinated program of Venus exploration will maximize the scientific return of those missions and set the stage for yet more ambitious projects to follow.

Finding: The key to long-term exploration of Venus is a dedicated, sustainable NASA Venus Exploration Program.

Finding: Making the identification and marketing of a compelling statement that motivates continued Venus exploration a near-term priority for the Venus community would be a potent tool for advocating for a Venus Exploration Program.

Path Forward: **The Venus community should actively work to demonstrate the scientific importance, value, and need for a Venus Exploration Program to as broad a set of stakeholders as possible between now and the start of the next planetary science Decadal Survey.**

Path Forward: **Such a Venus Exploration Program could be catalyzed by the early results of the triad of upcoming missions and others, so planning to put this framework in place by the early 2030s should start now.**