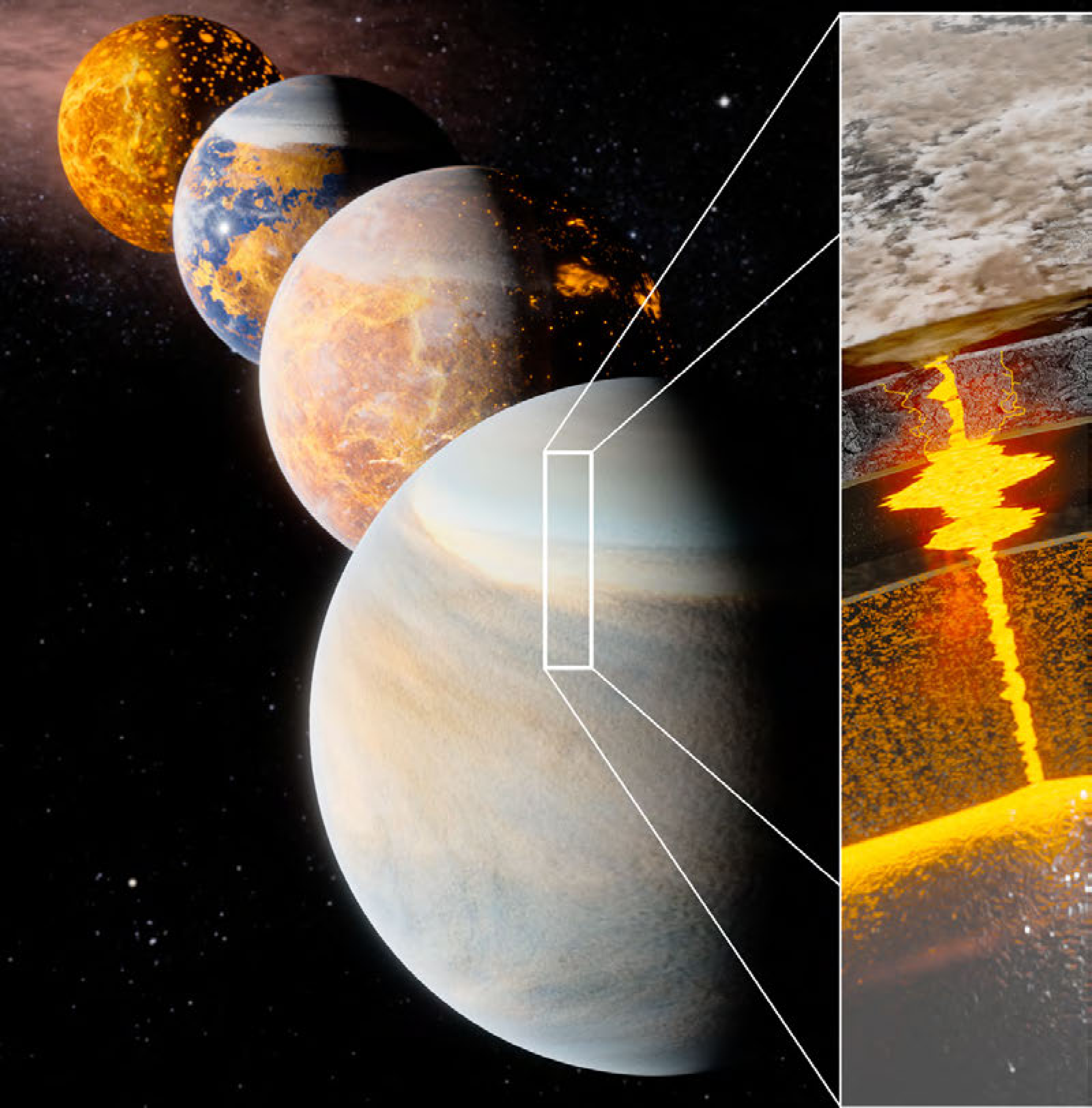
VENUS EXPLORATION ANALYSIS GROUP 2019

VENUS GOALS, OBJECTIVES, AND INVESTIGATIONS



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At the VEXAG meeting in November 2017, it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major documents were selected to be updated: (1) the Goals, Objectives and Investigations for Venus Exploration: (GOI) document, providing scientific priorities for Venus, (2) the Roadmap for Venus Exploration that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) the Technology Plan for future Venus missions. Here we present the 2019 version of the VEXAG Goals, Objectives and Investigations for Venus Exploration.

Prepared by the VEXAG GOI Focus Group: Joseph O'Rourke and Allan Treiman (Co-Chairs), Giada Arney, Paul Byrne, Lynn Carter, Darby Dyar, James Head III, Candace Gray, Stephen Kane, Walter Kiefer, Kevin McGouldrick, Laurent Montesi, Chris Russell, and Suzanne Smrekar.

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VEXAG Charter. The Venus Exploration Analysis Group (VEXAG) is NASA's community-based forum designed to provide scientific input and technology development plans for planning and prioritizing the exploration of Venus over the next several decades. VEXAG is chartered by NASA's Planetary Science Division (PSD) in the Science Mission Directorate (SMD) and reports its findings to NASA. Open to all interested scientists, VEXAG regularly evaluates Venus exploration goals, scientific objectives, investigations, and critical measurement requirements, including recommendations for the *NRC Decadal Survey* and the *Solar System Exploration Strategic Roadmap*.

1.0 Executive Summary

Venus and Earth are often described as twins. Their sizes and densities are nearly identical, and they are much larger than the other terrestrial planetary bodies of our solar system. Yet past exploration missions reveal that Venus is hellishly hot, devoid of oceans, apparently lacking plate tectonics, and bathed in a thick, reactive atmosphere. A less Earth-like environment is hard to imagine. When and why did Venus and Earth's evolutionary paths diverge? Did Venus ever host habitable conditions? These fundamental and unresolved questions drive the need for vigorous new exploration of Venus. The answers are central to understanding Venus in the context of terrestrial planets and their evolutionary processes. Critically, Venus provides important clues to understanding our planet—does hot, dry Venus represent the once and future Earth? Current and future efforts to locate and characterize planetary systems beyond our Solar System (e.g., the Kepler mission and the Transiting Exoplanet Survey Satellite) are aimed at Earth-size planets in the "habitable zones" of their parent stars. Precisely because it may have begun so like Earth, yet evolved to be so different, Venus is the planet most likely to yield new insights into the conditions that determine whether a Venus-sized exoplanet can sustain long-lived habitability.

The planetary science community has consistently identified Venus as a high-priority destination for scientific exploration. In the latest Decadal Survey (*Visions and Voyages for Planetary Science in the Decade 2013–2022*, National Research Council, 2011), Venus was listed as an "important object of study" in all three crosscutting themes (building new worlds, planetary habitats, and workings of solar systems). The Decadal Survey recommended the Venus In Situ Explorer as one of seven candidate missions for New Frontiers 4 and 5 and the Venus Climate Mission as one of five candidate Flagship missions. The midterm review of NASA's progress towards implementing the Decadal Survey found that programmatic balance in selected missions is vital to achieving investigations of comparative planetology.

Exciting Venus research has been ongoing since 1994, the end of the last US mission to Venus, extending to the recent Venus Express (ESA) and Akatsuki (JAXA) missions. In particular, the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) instrument on Venus Express (VEX) provided tantalizing evidence that tesserae terrains are composed of felsic rock—suggesting that they formed in the presence of abundant liquid water. Laboratory simulations show that plume-induced subduction on Venus could serve as an analog for the initiation of plate tectonics on the early Earth. Akatsuki has revealed fascinating features in the atmosphere such as planetary-scale standing gravity waves at the cloud tops that are associated with specific topographic features and local times. Conditions similar to those that led to the emergence of life on Earth may have occurred on Venus, but the surface today is too hot for terrestrial life and the clouds are cooler but extremely acidic.

Through an extended process including input from the science community at three town hall meetings and a workshop at LPSC in 2019, the VEXAG community has developed this list of Scientific Goals, Objectives, and Investigations. They are intended to address the priorities of the *Visions and Voyages* (National Research Council, 2011) Decadal Survey for 2013-2022 and to motivate future efforts. In particular, NASA's future exploration of Venus should strive toward three non-prioritized Goals:

Goal #1. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-sized (exo)planets,

Goal #2. Understand atmospheric composition and dynamics on Venus, and

Goal #3. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

This document describes the six Objectives and 23 Investigations that support these goals. Every Investigation was judged to be technically and programmatically feasible and scientifically valuable. Collectively, they support a sustained program of Venus exploration would unveil the workings of Earth's nearest neighbor with broad scientific implications for our Solar System and beyond.

2.0 VEXAG Goals, Objectives, and Investigations (GOI)

Table 1 summarizes this entire report. Because understanding Venus as a planetary system requires progress in many scientific areas, Goals and Objectives are not prioritized. Investigations are typed as **Essential (1)**, **Important (2)**, or **Targeted (3)** based on their relationship to the corresponding Objective. Completion of all Essential Investigations fundamentally addresses their Objective. Important Investigations address many aspects of their Objective and provide valuable context for other Investigations. Targeted Investigations address particular aspects of an Objective that significantly contribute to our overall understanding of Venus. Investigations with the same ranking have the same level of priority. **All listed Investigations are deemed to be significant and worthy of programmatic consideration.**[1]

Potential Investigations that were judged as having less than high scientific value are omitted entirely from this report. Investigations that would have high merit but are not technically feasible within the timescale of the VEXAG "Roadmap for Venus Exploration" are not included in Table 1, although some of them are discussed in Appendix 1 of this report.

Investigations from the 2016 VEXAG GOI are included in the current version (Appendix 2). However, the 2016 Goals focused separately on 1) the atmosphere, 2) surface and interior processes, and 3) the atmosphere-surface interface. The 2019 VEXAG GOI blends Investigations of different focus areas to achieve overarching Goals and has been iterated with other VEXAG Focus Groups to serve as the foundation for the VEXAG Roadmap and Technology reports.

[1]Because this document is being written in anticipation of a new Decadal Survey for 2023 and beyond, it intentionally avoids specific linkages to the old *Visions and Voyages* document. However, Appendix B of this document relates our Goals to the Goals of the 2014 VEXAG GOI document, and such mappings can be found therein.

Table 1. VEXAG Goals, Objectives, and Investigations

Goal	Objective	Investigation
I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.	A. Did Venus have temperate surface conditions and liquid water at early times?	**HO. Hydrous Origins (1).** Determine whether Venus shows evidence for abundant silicic igneous rocks and/or ancient sedimentary rocks.
		RE. Recycling (1). Search for structural, geomorphic, and chemical evidence of crustal recycling on Venus.
		AL. Atmospheric Losses (2). Quantify the processes by which the atmosphere of Venus loses mass to space, including interactions between magnetic fields and incident ions and electrons.
		MA. Magnetism (3). Characterize the distribution of any remanent magnetism in the crust of Venus.
	B. How does Venus elucidate possible pathways for planetary evolution in general?	**IS. Isotopes (1).** Measure the isotopic ratios and abundances of D/H, noble gases, oxygen, nitrogen, and other elements in the atmosphere of Venus.
		LI. Lithosphere (1). Determine lithospheric parameters on Venus that are critical to rheology and potential geodynamic transitions, including: stress state, water content, physical structure, and elastic and mechanical thicknesses.
		HF. Heat flow (2). Determine the thermal structure of the lithosphere of Venus at present day and measure in situ heat flow.
		CO. Core (2). Measure the size of the core of Venus and determine whether it remains partially liquid.

Table 1 (continued, a). VEXAG Goals, Objectives, and Investigations

Goal	Objective	Investigation
II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus?	**DD. Deep Dynamics (1).** Characterize the dynamics of the lower atmosphere (below about 75km) of Venus, including: retrograde zonal super-rotation, meridional circulation, radiative balances, mountain waves, and transfer of angular momentum.
		UD. Upper Dynamics (1). In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.
		MP. Mesoscale Processes (2). Determine the role of mesoscale dynamics in redistributing energy and momentum throughout the atmosphere of Venus.
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	**RB. Radiative Balance (1).** Characterize atmospheric radiative balance and how radiative transport drives atmospheric dynamics on Venus.
		IN. Interactions (1). Characterize the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere.
		AE. Aerosols (2). Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.
		UA. Unknown Absorber (2). Characterize the unknown short-wavelength absorber in the upper atmosphere of Venus and its influence on local and global processes.
		OG. Outgassing (3). Determine the products of volcanic outgassing on Venus and their effects on atmospheric composition.

Table 1 (continued, b). VEXAG Goals, Objectives, and Investigations

Goal	Objective	Investigation
III. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.	A. What geologic processes have shaped the surface of Venus?	**GH. Geologic History (1).** Develop a geologic history for Venus by characterizing the stratigraphy, modification state, and relative ages of surface units.
		GC. Geochemistry (1). Determine elemental chemistry, mineralogy, and rock types at localities representative of global geologic units on Venus.
		GA. Geologic Activity (1). Characterize current volcanic, tectonic, and sedimentary activity that modifies geologic units and impact craters and ejecta on Venus.
		CR. Crust (2). Determine the structure of the crust of Venus in three dimensions and thickness across the surface.
	B. How do the atmosphere and surface of Venus interact?	**LW. Local Weathering (1).** Evaluate the mineralogy, oxidation state, and changes in chemistry of surface-weathered rock exteriors at localities representative of global geologic units on Venus.
		GW. Global Weathering (2). Determine the causes and spatial extents of global weathering regimes on Venus.
		CI. Chemical Interactions (3). Characterize atmospheric composition and chemical gradients from the surface to the cloud base both at key locations and globally.

3.0 Descriptions of the Goals, Objectives, and Investigations

3.1. Goal I: Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.

Like Earth, Venus may have hosted oceans of liquid water for billions of years (e.g., Way et al. 2016). Alternatively, these sister planets may have followed distinct evolutionary paths from the birth of the Solar System (e.g., Gillmann et al. 2009; Hamano et al. 2013). Because it may have begun so similar to Earth, yet evolved to be so different, Venus is the planet most likely to yield new insights into the conditions that determine whether a Venus-sized exoplanet can sustain long-lived habitability (e.g., Kane et al. 2018; Kane et al. 2014).

3.1.1. Objective I.A. | Did Venus have temperate surface conditions and liquid water at early times? The amount of water that Venus received during and after its accretion remains unknown. Standard models imply that Venus and Earth received similar amounts of water from comets and bodies that formed in the vicinity of Jupiter (e.g., Rubie et al. 2015). Temperate surface conditions would represent an important evolutionary path for Venus because of the implications for habitability of ancient Venus and Venus-sized exoplanets at present day.

<u>3.1.1.1. Investigation I.A.HO. Hydrous Origins (Essential):</u> Water is important to the geologic evolution and potential habitability of Venus. Although liquid surface water is now unstable, its presence may have been required to form many rock types on Venus, such as granitic rocks suggested for some tesserae (e.g., Gilmore et al. 2017; Gilmore et al. 2015; Mueller et al. 2009). Formation of Earth's large granitic continents required water in magmatic source regions in the crust and mantle (e.g., Campbell and Taylor 1983). Similarly, some sedimentary rocks cannot form without liquid water, such as those rich in sulfate and halide (e.g., evaporites), silica (e.g., in hot spring deposits and hardpans), or carbonates. Even deposits of clastic sediments can preserve physical signatures of transport by liquid water (e.g., delta deposits observed from orbit on Mars).

Remote sensing and in situ analyses may reveal signatures of hydrous origins. Granites have lower visible near-infrared (VNIR) emissivity than basalts. This can be measured through several spectral 'windows' (near 1 μm) in Venus' thick atmosphere (Gilmore et al., 2015; Hashimoto and Sugita, 2003). Similarly, low emissivity may reveal sediments rich in evaporites, silica, or carbonates. Emissivity could be measured from orbit, aerial, or surface platforms. Physical characteristics of clastic sedimentary systems may be discernable from orbital or aerial radar with high spatial resolution. Landers can provide detailed determinations of rock type and physical inter-relationships using high-resolution imagers and chemical analysis instruments (e.g., x-ray fluorescence, gamma ray spectrometry, or LIBS). Landers could potentially remove surface coatings caused by chemical weathering to determine the detailed mineralogy of a Venus rock.

<u>3.1.1.2. Investigation I.A.RE. Recycling (Essential):</u> Crustal recycling occurs when surface and near-surface materials are transferred by subduction and/or delamination to the interior, participating in melt production and chemical evolution of the lower crust and mantle. Identification of widespread ongoing or ancient crustal recycling on Venus would have profound implications for our understanding of thermal, chemical, geological, and atmospheric evolution on Venus and on terrestrial planets in general (e.g., Elkins-Tanton et al., 2007). Localized plume-induced subduction has been proposed to operate on Venus (Davaille et al., 2017), and there is evidence of substantial lateral mobility of some parts of the crust. Crustal recycling is predicted to result in lavas with distinctive geochemical

signatures, and numerous regions of tesserae on Venus have been hypothesized to be continental-like material formed during an earlier era of crustal recycling (e.g., Gilmore et al., 2017; Gilmore et al., 2015). Currently available gravity, radar image, and topographic data are insufficient to determine whether these processes operate more widely and/or took place in the geological past.

No single type of observation by itself can definitively establish crustal recycling on Venus. Global radar images, topography, and gravity data at high resolution could help search for geomorphological evidence of crustal recycling, especially if augmented by imagery and topography at higher resolutions at areas of interest. In situ measurements by a landed platform of lava flows could test for chemical evidence for recycling (enrichment or depletion of incompatible elements such as K, P, Zr, rare-earth elements, etc.). Similarly, direct chemical analyses of Si abundance of tessera terrain would test if that material corresponds to Earth-like continental crust. Finally, detections of seismic activity on Venus with orbital, aerial, or landed assets may help constrain models of recent or ongoing crustal recycling.

3.1.1.3. Investigation I.A.AL. Atmospheric Losses (Important): Atmospheric loss processes on Venus provide the upper boundary condition for the evolution of its atmosphere. The high D/H ratio in Venus' atmosphere (~100 times that of Earth's oceans) suggests it may once have held an ocean's worth of water that has since been mostly lost to space (e.g., Donahue et al. 1982). Because the H escape velocity is too high for thermal or photochemical processes to attain non-thermal escape driven by the solar wind is the most important process for atmospheric loss today (e.g., Airapetian and Usmanov 2016; Brain et al. 2016; Chassefière 1996; Shizgal and Arkos 1996). Intense solar wind disturbances, such as those generated by co-rotating interaction regions (CIRs) and interplanetary coronal mass ejections (ICMEs), are known to increase atmospheric escape. Observations of Venus' ion outflow during solar disturbances show that the escape flux can increase by orders of magnitude, especially during ICME events (Luhmann et al., 2008). Additionally, changes in the interplanetary magnetic field (such as those associated with CIRs) lead to magnetic reconnection on the Venusian dayside that further drives atmospheric loss. Atmospheric loss via ambipolar diffusion always occurs and is much more efficient at Venus than at any other terrestrial planet (e.g., Collinson et al. 2016).

Despite insights from Pioneer Venus Orbiter (PVO) and VEX, these loss processes have not been sufficiently characterized. Simultaneous observations of both the upstream solar wind and the Venusian thermosphere and ionosphere over the full range of local times and solar zenith angles would build a more complete picture of atmospheric erosion, especially if acquired during solar minimum and maximum. Relevant instruments for this Investigation include but are not limited to electron spectrometers, ion mass spectrometers, neutral particle detectors, UV and visible spectrographs and imagers, solar energetic particle (SEP) detectors, Langmuir probes, and magnetometers. Some of these measurements could be conducted with dedicated spacecraft or opportunistic flyby instruments (e.g., multiple SmallSats). For example, these could be used to image dayglow, aurora, and sample plasma conditions from ~150 km out to several Venus radii at the Sun-Venus L1 Lagrange point, as well as the upstream solar wind environment.

3.1.1.4. Investigation I.A.MA. Magnetism (Targeted): Venus has no intrinsic magnetism today but might have once hosted a dynamo. Its rotation is fast enough for the

Coriolis force to affect any convective fluid flows in the core (e.g., Stevenson 2010). Detection of crustal remanent magnetism would show that a dynamo existed in the past and that the surface has remained cooler than the blocking temperatures of magnetic minerals. For example, simulations predict that if the core of Venus was initially "Earth-like" (hot and chemically homogeneous), then a dynamo might have operated <750 ma (Gillmann and Tackley, 2014; O'Rourke et al., 2018). Common magnetic minerals such as magnetite and hematite may retain thermoremanent magnetization for billions of years at Venus surface temperatures (O'Rourke et al., 2019). Data from PVO and VEX rule out crustal magnetization that is both strong and has typical coherence wavelengths >150 km northwards of 50° South latitude only (e.g., Russell et al. 2007). Venera 4 measured magnetic fields down to ~25 km altitude above Eistla Regio and failed to detect any crustal remanence.

Orbiters could still detect fields produced by strong, large-scale crustal magnetization southward of 50° South latitude. Magnetization that is relatively weak and coherent over >150 km and/or strong and coherent over smaller scales could exist anywhere on Venus except at the Venera 4 landing site. Magnetometer measurements at low altitudes, such as from an aerial platform, would be needed because magnetic field power decreases rapidly (as distance cubed) at altitudes above the coherence wavelength of the source magnetization. While a non-detection would permit multiple scenarios (e.g., no dynamo and/or a hotter surface in the past), this Investigation is Targeted because any detection of crustal remanent magnetization would provide a unique constraint on atmospheric loss processes and recent climate history.

3.1.2. ***Objective I.B. | How does Venus elucidate possible pathways for planetary evolution in general?*** Only two Venus-sized planets made of rock and metal exist in our Solar System, but myriad examples of Venus-sized exoplanets are being discovered and characterized with new telescopes (e.g., Kane et al. 2014; Schaefer and Fegley 2011). Our general model for the long-term evolution of terrestrial exoplanets cannot rest on a foundation of fundamental ignorance about Earth and Venus. While Objective I.A. focused on a uniquely compelling evolutionary scenario, the following Investigations consider many possibilities (e.g., Glaze et al. 2018; Taylor et al. 2018).

3.1.2.1. Investigation I.B.IS. Isotopes (Essential): The isotopic composition of Venus' atmosphere should preserve significant clues to the accretion, differentiation, and early evolution of the planet (e.g., Chassefière et al. 2012). Interpretation of the D/H ratio has substantial uncertainties at present (e.g., Greenwood et al. 2018). Other atmospheric constituents such as N, C, Cl, and the heavy noble gases constrain the abundances, sources, and compositions of volatiles in Venus' early atmospheres. The isotopic compositions of these gases will help define the sources of Venus' volatiles (e.g., comets versus asteroids) and the extent to which they were affected by atmospheric loss processes, surface and interior outgassing, and (more speculatively) active biology. Xenon is critical to measure because the terrestrial planets appear to have tapped distinct sources (e.g., Pepin and Porcelli 2002). The same processes that produced the high D/H ratio on Venus may have depleted atmospheric Xe. In the mantle, radioactive decay of ^{40}K produces ^{40}Ar and decay of U and Th produces ^{4}He. Measurements of atmospheric ^{40}Ar and ^{4}He thus constrain the integrated amount of volcanic outgassing from the interior (e.g., Kaula 1999; Namiki and Solomon 1998). Oxygen isotopes could reveal whether Venus and Earth formed from the same reservoir of material. A finding of similar isotopic ratios for Earth and Venus versus

Mars would relax a key constraint on models of the origin of the Moon (e.g., Mastrobuono-Battisti et al. 2015).

Mass spectrometer measurements of atmospheric constituents are required to fulfill this Investigation. Analyses of material from deeper than the homopause, where the atmosphere is well-mixed, would be most useful (Chassefière et al., 2012). Any asset that enters the atmosphere—aerial platforms or atmospheric skimmers, probes and landers with heritage from Pioneer Venus or Venera/Venera Galley (VeGa), respectively—could potentially deploy a useful mass spectrometer.

3.1.2.2. Investigation I.B.LI. Lithosphere (Essential): Venus shows no evidence for the global regime of plate tectonics observed on Earth, implying that the lithosphere of Venus does not sustain localized deformation over long spatial and temporal scales. The current dynamical regime of Venus—whether it involves stagnant-lid convection, heat pipes, episodic overturns, or another mode of mantle convection—remains poorly understood (e.g., Smrekar et al. 2018). Determining key lithospheric parameters is considered an Essential Investigation because the lithosphere provides the upper boundary condition for mantle convection and links interior activity with surface observables.

High-resolution radar imagery and altimetry with global coverage would constrain lithospheric rheology through quantitative analyses of stress states, tectonic faulting, and volcanism. Electromagnetic sounding could determine whether the water content of the lithosphere is more or less than a few hundred parts per million (Grimm et al., 2012). These datasets would constrain models of processes that support topography. Elastic thicknesses would be retrieved by modeling admittance and/or flexural bending seen in topography. Mechanical thicknesses would then be derived and thus used to estimate the thermal gradient in the lithosphere that prevailed when elastic flexure first occurred. Existing estimates of elastic thickness from gravity data often have large uncertainties due to the limited accuracy and resolution of the present gravity field (e.g., Anderson and Smrekar 2006). Values from modeling topographic bending are currently limited to a small subset of volcanoes and coronae where flexure can be observed (e.g., Johnson and Sandwell 1994; O'Rourke and Smrekar 2018). Finally, seismology conducted from orbital, aerial, and/or landed platforms could determine the physical structure and deformation processes of the lithosphere (e.g., Cutts et al. 2018).

3.1.2.3. Investigation I.B.HF. Heat Flow (Important): Although models of mantle convection often predict that total heat flow through the lithosphere to the surface of Venus is roughly half of the measured value for Earth (Armann and Tackley, 2012; Driscoll and Bercovici, 2014; Gillmann and Tackley, 2014), these models remain unvalidated by direct observations. Measuring the lithospheric heat flow (e.g., thermal gradient times conductivity) would help evaluate models of interior convection. This Investigation is a benchmark for models of geodynamic evolution in synergy with other constraints.

In-situ measurements would provide the highest-quality heat flow measurements if the seasonal/daily temperature variation is quantified through coupled studies of surface brightness temperature. Selecting targeted locations that enable meaningful comparisons with models of mantle convection requires understanding the geologic history and relative ages of surface units. Electromagnetic sounding conducted from an aerial platform could determine lithospheric thermal gradients over larger areas (Grimm et al., 2012). Lightning-caused Schumann resonances are capable of penetrating to depths of ~50–100 km if the lithospheric water content is less than a few hundred parts per million. Retrieving thermal gradients in shallow regions is potentially tractable even if the lithosphere is relatively wet. Any measurement of present-day heat flow and thermal structure would complement constraints on past heat flow from elastic thickness measurements.

3.2.1.4. Investigation I.B.CO. Core (Important): The size and physical state of the core place key constraints on models of the thermal evolution of Venus. Energy from giant impacts (kinetic) and rapid accretion (gravitational) is expected to produce a completely molten core initially. The relative sizes of the silicate mantle and the metallic core constrain their compositions and the thermodynamic conditions of accretion through the abundance of light elements (e.g., silicon and oxygen) in the core (e.g., Rubie et al. 2015; Jacobson et al. 2017). Two basic measurements of Venus are lacking: its total moment of inertia and the radius of the core (e.g., Smrekar et al. 2018). Existing measurements of the tidal Love number also are arguably too imprecise to distinguish between a partially liquid core and one that has finished solidifying (Dumoulin et al., 2017).

Orbiters with modern radio tracking would provide improved measurements of the tidal Love number with the required precision. The moment of inertia of Venus may be constrained even without spacecraft missions. Simultaneous observations of radar echoes with the Goldstone Solar System Radar and the Green Bank Telescope allow measurement of the instantaneous spin orientation of Venus. Tracking the instantaneous spin orientation over years and decades enables a measurement of the moment of inertia. As planned for the NASA InSight mission on Mars, a single station with radio science may measure the radius of the core given a sufficient lifetime.

3.2. Goal II: Understand atmospheric dynamics and composition on Venus

The atmosphere of Venus is a planet-sized heat engine. Energy deposition and the efficiency with which that energy is distributed throughout the planet are key constraints on potential habitability. For Earth, a fleet of in situ and orbital platforms builds the complete, four-dimensional picture of atmospheric evolution. These Investigations divide the atmosphere of Venus into altitude-based areas, but these areas ultimately remain coupled in a planetary system.

3.1.1. Objective II.A. | What processes drive the global atmospheric dynamics of Venus?

Many fundamental atmospheric characteristics of Venus are poorly understood, including the global cloud cover and retrograde zonal super-rotation (RZS). Winds on Venus flow primarily from east to west at almost all altitudes below ~85 km. Wind speeds reach a peak in magnitude just above the cloud tops. Above ~75 km altitude, winds transition to a subsolar to antisolar (SSAS) flow, before transitioning back to RZS in the upper thermosphere (Sánchez-Lavega et al., 2017).

3.1.1.1. Investigation II.A.DD. Deep Dynamics (Essential): The super-rotation of Venus' atmosphere has been known from cloud top observations since the early 20th Century. Full understanding of the RZS structure and mechanisms for its maintenance remains elusive. Variability in the form of zonal jets has been inferred from Akatsuki observations. Global-scale waves observed by Akatsuki's Longwave Infrared camera are tied to the crests of continent-sized land masses and recur regularly at similar times-of-day (Fukuhara et al., 2017; Kouyama et al., 2017). Similar waves may have been seen by the VeGa balloons near the dawn terminator while flying over Aphrodite Terra (Blamont et al., 1986). These orographic waves demonstrate the importance of surface-atmosphere interactions for the dynamics of Venus and its atmosphere. Generation and dissipation of the orographic waves has been inferred to produce measurable changes in the rotation rate of the solid planet, and to affect solar-atmosphere interactions even in the deep atmosphere (Navarro et al., 2018). Understanding RZS will be a milestone advance for atmospheric sciences in general, and provide tests of exotic behavior in models of exoplanetary atmospheres.

The deep atmosphere of Venus is defined in this context to be the portion of the atmosphere that is beneath the cloud tops, i.e., below ~75 km altitude. This Investigation is Essential because a critical transition in atmospheric dynamics occurs here, according to measurements of wind speed and temperature. Almost nothing is known about atmospheric composition and dynamics very near the surface (below 22 km). Above ~75 km altitude, the primary means of data acquisition would most likely come from an orbital platform. Below this altitude, measurements should be possible from both in situ and remote platforms. Simultaneous observations of radar echoes with the Goldstone Solar System Radar and the Green Bank Telescope allow measurement of the instantaneous spin period of Venus, which was not achieved with either Magellan or Venus Express. Tracking the instantaneous length-of-day provides a time history of variations in atmospheric angular momentum that can be used to constrain global circulation models.

3.1.1.2. Investigation II.A.UD. Upper Dynamics (Essential): The RZS must also be understood at planetary scales. RZS flow loses strength in the upper mesosphere, so SSAS flow dominates near 100 km. However, RZS flow becomes prevalent again in the thermosphere for unknown reasons (e.g., Gérard et al. 2017). Flow dynamics in the thermosphere can be constrained through observations of nightglow and auroral emission. One of the brightest Venusian nightglow features is the 1.27 µm O_2 ($^1\Delta_g$) emission, which is strongest at ~99 km elevation near the antisolar point. VEX observations show that this nightglow follows the SSAS flow. However, simultaneous observations of O_2 ($^1\Delta_g$) and the NO UV bands (~115 km elevation) reveal that the NO bands are shifted three hours away from local midnight towards the dawn sector, indicating a recurrence of the RZS flow between those elevations (Gérard et al., 2009; Stiepen et al., 2013). Auroral OI emission (at 130.4 nm) is also offset towards the dawn sector (Phillips et al., 1986). Offsets are expected between the OI UV emission and the OI auroral emission that is present during solar storms, but no spatial mapping has been conducted.

Recent studies suggest that the ionosphere and neutral atmosphere are more intimately connected than previously believed (e.g., Futaana et al. 2017). Measurements are needed of auroral and other excited gas emissions driven by solar processes as well as by the solar wind in order to understand the connections between the solar wind and the Venusian atmosphere. Instruments needed to study the Venusian atmosphere and the solar wind via remote sensing and in-situ measurements include but are not limited to electron spectrometers, ion mass analyzers, ion and neutral mass spectrometers, energetic neutral atom detectors, UV and visible spectrographs and imagers, SEP detectors, Langmuir probes, and magnetometers.

3.1.1.3. Investigation II.A.MP. Mesoscale Processes (Important): The previous two Investigations target global scale processes and observations according to vertical spatial domain (above and below an altitude of ~75 km). Investigation of processes at smaller scales (mesoscale) is important because they drive planetary atmosphere dynamics at both larger and smaller scales. Adequate general circulation models of a planetary atmosphere must include reliable parameterizations of these “sub-grid-scale” processes, mandating new observational constraints from Venus.

Critical mesoscale processes include the behavior and evolution of convective cells, horizontal and vertical wave propagation, and other mesoscale structures. These processes can be observed from orbit, as demonstrated by the discovery of numerous mesoscale features in both Venus Express and Akatsuki data (Peralta et al., 2019, 2017). The rate and global distribution of lightning is a proxy for a certain rate of convective activity that is necessary to drive charge exchange (Takahashi et al., 2008). Direct in-situ measurement of the local dynamics of isolated convective structures and/or wave propagation would also contribute to this Investigation. However, degeneracies between spatial and temporal variations would remain—as are present in the meteorological data from the VeGa balloons—in the absence of simultaneous measurements from orbiters and aerial platforms.

3.1.2. Objective II.B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance? The atmosphere of Venus is a coupled chemical, radiative, and dynamical system. The composition and evolution of the atmospheric constituents are strongly regulated by chemical processes in the highly complicated, sulfur-based chemical networks. Yet, significant questions remain regarding the identities and/or the sources and sinks for many of these constituents.

3.1.2.1. Investigation II.B.RB. Radiative Balance (Essential): Gradients in the upwelling and downwelling radiative fluxes, in both incident solar and emitted planetary radiations, determine the heating/cooling rates that drive atmospheric dynamics. These gradients are determined by absorbers and scatterers of both shortwave and longwave radiation that are distributed throughout the atmosphere, which are involved in a variety of physical and chemical interactions. Although the local radiative balance has been measured many times to reasonable precision (e.g., Pioneer Venus, Venera, and VeGa missions), a mismatch remains between the measured radiative and dynamical parameters of the Venus atmosphere and those produced by models (Crisp, 1989; Limaye et al., 2018a). What is the magnitude of the influence of variability of the numerous radiatively active species, and cloud microphysics and opacity on the radiative balance of Venus? To what extent does this distribution of radiative sources and sinks drive the tropospheric dynamics?

Direct, in-situ measurement of spectrally resolved (or integrated) upwelling and downwelling radiances on both the nightside and dayside can support this Investigation. Probes, landers, and/or mobile aerial platforms could make relevant measurements. The utility of these measurements increases substantially with the number and lifetimes of platforms, and with global context. High spectral resolution, full spectrum measurements of emitted and reflected radiation would substantially contribute to this Investigation. Orbital assessments of radiative balance would benefit from improving the foundational models of atmospheric constituents.

3.2.2.2. Investigation II.B.IN. Interactions (Essential): Constituents of the atmosphere of Venus comprise a highly coupled system involving sulfur and carbon chemistry, aerosol microphysics, and possibly even biological activity. Agreement between chemical models of the Venus atmosphere and observed vertical profiles of multiple participating constituents is necessary for constraining models of radiative balance and atmospheric evolution. Examples of unresolved questions include the relative roles of OCS and SO_2 as sulfur donors to the sulfurohydrologic cycle of sulfuric acid generation, as well as the role of H_2O in that process (Marcq et al., 2018). Photochemistry and thermochemistry in Venus' atmosphere are quite dissimilar to those on Earth, and have not been fully explored in the lab. Finally, the chemistry of supercritical CO_2 in the deep atmosphere remains unexplored, though recent research suggests it may explain why the temperature profile measured by the VeGa probe is stable against convection in the lowermost atmosphere (Lebonnois and Schubert, 2017).

An orbiter capable of acquiring high spectral resolution measurements across a broad wavelength region and retrieving high precision vertical profiles of chemically relevant species could make substantial progress towards achieving this Investigation, especially when coupled with improved models of atmospheric chemistry in the Venus environment. In situ aerial platforms could make substantial progress on understanding the aqueous chemistry, as has been done for Earth. Lightning has been mapped on the nightside. Statistical assessments of the presence and distribution of lightning, mapped on the nightside by Pioneer Venus and at polar latitudes by Venus Express in the Venus atmosphere, would constrain the effects of lightning discharges on atmospheric constituents. Finally, landers and descent probes capable of simultaneously measuring meteorological parameters and the mixing ratio of CO_2 (and other species) in the lowest ~10 km could study supercritical CO_2.

3.2.2.3. Investigation II.B.AE. Aerosols (Important): This Investigation studies the impact of aerosols on the Venus greenhouse effect, as well as on its remotely observable properties. Aerosols are an integral part of the atmospheric chemical system as both active and passive constituents (Titov et al., 2018). Spherical particles of highly concentrated sulfuric acid with typical radii of 1 μm are the primary aerosol in the upper clouds, but the exact nature of Venusian aerosols is incompletely known. A submicron mode of particles is known to exist in and below the upper, middle, and lower clouds, but its size distribution at all altitudes remains poorly constrained. In the upper clouds, the composition of aerosol particles has been assumed but never proved to be sulfuric acid. In and below the lower and middle clouds, the composition of this submicron aerosol mode remains similarly unknown. Finally, particles with the largest inferred sizes remain controversial. Their night-side, near-infrared inhomogeneities are attributed largely to variations in the Mode 3 population, but their existence remains unconfirmed and their composition unknown (Barstow et al., 2012; Knollenberg and Hunten, 1980).

In-situ nephelometer and mass spectroscopy of cloud aerosols would reduce uncertainties in aerosol size distributions and compositions. Observations at altitudes throughout the cloud column are key because different populations of aerosols occur at different altitudes.

3.2.2.4. Investigation II.B.UA. Unknown Absorber (Important): Short-wavelength visible and near-ultraviolet light are unaccountably absorbed in Venus' upper atmosphere. The effects of this unknown absorber are strongest in the near-ultraviolet, but are apparent well into at least the wavelengths of visible light. The unknown absorber varies in strength over space and over a wide range of timescales. The unknown absorber is responsible for at least half of the deposition of solar insolation into the atmosphere (Crisp, 1986).

Numerous candidate absorbers have been proposed, including sulfur allotropes (S_x), iron chlorides ($FeCl_3$), and OSSO and its isomers. The unknown absorber might not be a single species because OSSO does not absorb enough near 400 nm to match observations. A biological origin for the unknown absorber in the "habitable zone" of the atmosphere has been suggested by comparison to the spectral properties of terrestrial acidophilic organisms (e.g., Limaye et al. 2018b).

Mass spectrometry of atmospheric material in the region of the unknown absorber is the measurement most likely to accomplish this Investigation. The platform most appropriate to carry this mass spectrometer is likely a descent probe, or aerial platform. In addition, high-resolution spectroscopy from orbit or from an aerial platform can contribute to the investigation. In general, synergistic measurements from multiple platforms are desired.

3.2.2.5. Investigation II.B.OG. Outgassing (Targeted): This Investigation will determine whether volcanic outgassing affects atmospheric composition, which might provide insights into crustal composition and internal structure and dynamics. Indirect observations hint that Venus is volcanically active today. Overall, the surface has a young average age of ~750 Myr and hosts myriad volcanic surface features (Smrekar et al., 2018). Transient and high concentrations of SO_2 in the atmosphere and thermal anomalies on the surface have also pointed to currently active volcanism (e.g., Esposito et al. 1988). Massive H_2SO_4/H_2O clouds are most likely the products of volcanic outgassing of SO_2 in the past ~10–50 Myr (Bullock and Grinspoon, 2001). The VIRTIS instrument on VEX measured near-IR surface emissivity anomalies interpreted as a lack of surface weathering at fresh volcanic flows on and near several massive shield volcanoes (Smrekar et al., 2010).

Direct imaging of hot spot volcanism and volcanic lakes at near-IR wavelengths and SAR interferometry from orbit would characterize the ongoing rate of volcanism on Venus. Direct monitoring of heat from volcanic activity remains a viable, low-risk method to detect the ‘smoking gun’ of active volcanism on Venus. Spectroscopic remote sensing of transient gases in a volcanic plume (SO_2, H_2O) has also been suggested as an indirect means of sensing volcanic activity and outgassing. Aerial platform measurements acquired from beneath the clouds could be used to confirm the nature of events detected from orbited in images with five orders of magnitude better spatial resolution. In situ chemical measurements, including light isotope abundances, could help constrain the composition of outgassed materials.

3.3. Goal III: Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

Unveiling the past requires understanding the present. Although previous missions provided the first glimpses of the Venusian surface, many first-order questions regarding their interpretation and implications await answers, which motivates collecting higher-resolution imagery, topography, and many other datasets that are available for other terrestrial planets.

3.3.1. Objective III.A. | What geologic processes have shaped the surface of Venus? Since the Magellan mission, models for the geologic history of the surface have been spread between catastrophic and uniformitarian end-member scenarios. Moving beyond this controversy requires answering many basic questions about the present-day surface, including its stratigraphic history, composition, and potential for ongoing geologic activity.

3.3.1.1. Investigation III.A.GH. Geologic History (Essential): Developing a stratigraphic history for the sequence of geological events on Venus is crucial to provide a framework for understanding the processes that shaped the coupled evolution of the surface, interior, and atmosphere (e.g., Guest and Stofan 1999; Hansen and Lopez 2010; Ivanov and Head 2013; Ivanov and Head 2011; McGill 2004; Strom et al. 1994). Volcanism and tectonism are ultimately driven by processes in the interior of Venus, and volcanism also contributes to development of the atmosphere. Similarly, the history of tectonic activity constrains the style and temporal evolution of convection in the mantle. In addition, a stratigraphic history for Venus would facilitate comparisons with other terrestrial planets.

Key data sets for this Investigation are high-resolution radar imagery and topography. Magellan provided near global radar imaging at ~120–300 m/pixel and altimetry at ~8–25 km/pixel. Ideally, a follow-up mission would provide order-of-magnitude improvement in resolution in both radar images and altimetry. Global imaging coverage is desired to fully picture Venus' geologic evolution. A targeted survey could focus on mapping at high spatial resolution highland regions with obvious tectonic or volcanic features plus a representative fraction of the regional plains. The signal-to-noise ratio should be sufficiently large to detect variability that may be present in the radar dark plains. Infrared imaging of selected regions at relatively high spatial resolution from a variable altitude aerial platform, deployed below the cloud deck, would be complementary to the greater spatial coverage possible from an orbiter.

3.3.1.2. Investigation III.A.GC. Geochemistry (Essential): The surface chemistry and mineralogy of Venus remain poorly characterized. Chemical analyses provided by the Venera and VeGa missions, although they were engineering and scientific triumphs, do not permit detailed interpretations like those from rover analyses on Mars (e.g., Treiman 2007). In particular, Soviet x-ray fluorescence (XRF) analyses of major elements did not return abundances of Na, and their data on Mg and Al are little more than detections at the ~2σ level. Data for K, U, and Th (by gamma rays) are imprecise, except for one (Venera 8) with extremely high K contents (~4% K_2O) and one (Venera 9) with a non-chondritic U/Th abundance ratio. The landers did not return data on other critical trace and minor elements, like Cr and Ni. In addition, the Venera and VeGa landers sampled only materials from the Venus lowlands. Given all these ambiguous results, rock types that may indicate igneous provenance cannot be identified (e.g., Grimm and Hess 1997; Treiman 2007). Similarly, no information is currently available to identify Venus mineralogy (Gilmore et al., 2017).

3.3.1.3. Investigation III.A.GA. Geologic Activity (Essential): The relatively young surface age of Venus implies that Venus is geologically active. Key data sets are radar imaging and topography as well as seismic measurements (e.g., Smrekar et al. 2018). Comparison of radar imagery and altimetry from a future orbital mission with archival data from Magellan could detect surface changes over a period of several decades. Differential InSAR altimetry from a future orbiter could detect small topographic changes (≤10 cm vertically) due to active tectonism or volcanism that occur over the timescale of that orbiter mission. Seismic measurements via a long-lived lander of seismicity induced by active tectonism or volcanism would also be invaluable. Measurements by a single lander would be sufficient to detect such activity, but measurements by a network would enable more quantitative analysis of the activity. Because the rate of such activity is not known, this approach is enhanced by increasing the duration of seismic measurements. As demonstrated by Venus Express, fresh flows (i.e., with little chemical weathering) are observable with NIR spectroscopy from orbit (e.g., Shalygin et al. 2015; Smrekar et al. 2010). Experiments suggest these flows may be only years old.

Several types of supporting measurements also are possible. Coupling of surface motion into the thick Venus atmosphere can propagate pressure waves into the upper atmosphere that are detectable in high temporal resolution infrared images from orbit or by infrasound measurements from an aerial platform (e.g., Cutts et al. 2018; Stevenson et al. 2015). Volcanic flows temporarily raise the surface temperature, which could be measured by infrared or microwave radiometry. Observing this thermal signature is easiest for flows with high flux rates, which prevent the flow from crusting over. Outgassing associated with large explosive volcanic eruptions may temporarily create a disequilibrium in the atmospheric composition which could be measured by orbiters, atmospheric entry probes or sondes, and/or aerial platforms.

3.3.1.4. Investigation III.A.CR. Crust (Important): The crust of Venus has at least partially recorded the last billion years or so of tectonic and volcanic activity on the planet. Crustal thickness can constrain the total amount of magmatism, and variations related to location of more ancient materials like tessera or more recent units like rift zones can help quantify activity outside of the resurfacing event (e.g., Anderson and Smrekar 2006; James et al. 2013). Information about the structure of the crust, including the thickness of plains units and the penetration of faults at depth, are also crucial for reconstructing the history of geological activity on Venus and how it may have changed over time. Timing and volume of volcanic flows (e.g, Ivanov and Head 2013) and their interactions with impact craters (e.g., Herrick and Rumpf 2011; Strom et al. 1994) would constrain whether volatiles were released gradually or catastrophically from the interior.

Global radar images, topography, and gravity data collected by orbiters and/or aerial platforms at high precision and resolution would constrain the thickness and density structure of crustal units such as regional plains and volcanic flows. Improving the spatial resolution of global geological maps by one or more orders-of-magnitude would enable the delineation of individual lava flows, mapping individual fault blocks, and characterizing geologic contacts between volcanic and structural units, fundamentally transforming our understanding of volcanic and tectonic processes on Venus. Radar data in circular polarizations, as done by Arecibo and other planetary radars, would help quantify the thickness and grainsize of surface materials (e.g., volcanic deposits versus ejecta and/or regolith). Other geophysical techniques such as ground-penetrating radar (from orbital or aerial platforms) and seismology (from a surface instrument or detected in the atmosphere, which is strongly coupled to the ground) would provide strong constraints on the thickness and distribution of near-surface units on Venus.

3.2.3. Objective III.B. | How do the atmosphere and surface of Venus interact?

Temperatures of ~470°C and pressures ~90 bars near the surface ensure geologically rapid chemical reactions. Available data suggest that the deep atmosphere composition is not consistent with chemical equilibrium. However, significant uncertainties remain in the reactions that occur at the atmosphere-surface interface, the redox state of the atmosphere-surface boundary, and the concentrations and spatial variations of important trace gases near the surface.

3.2.3.1. Investigation III.B.LW. Local Weathering (Essential): The history of gas/fluid interactions between Venus' hot, dense CO_2-rich atmosphere and its surface materials is recorded in the minerals that have experienced such alteration. Laboratory and phase equilibria studies predict oxidation of primary igneous minerals to ferric oxides such as magnetite and hematite (e.g., Fegley et al. 1997; Zolotov 2018; Zolotov 2015). This investigation would search for the presence of anhydrous salt minerals such as anhydrite and possible presence of alteration phases from basaltic minerals. This would involve in situ instruments for mineralogy, including visible-mid-IR and Raman spectroscopies. Penetrating beneath surface alteration could provide valuable information on the depth of alteration and the underlying mineralogy.

3.2.3.2. Investigation III.B.GW. Global Weathering (Important): Among the most striking findings of the Magellan mission was the discovery of great differences in radar backscatter brightness with elevation (e.g., Pettengill et al. 1997): the highlands are significantly brighter than the lowlands. However, approaches to identifying candidate substances responsible for this dichotomy (e.g., Schaefer and Fegley 2004) depend on the assumed surface geochemistry and oxidation states, which are poorly known (e.g., Treiman 2007). Possible Investigations to resolve these questions are two-fold. Orbital spectroscopy utilizing the windows in the ~1 μm region may allow discrimination among key rock types (e.g., basalt vs. granite) and can distinguish among minerals responsible for radar backscatter variations with elevation, such as magnetite hematite, and pyrite (Gilmore et al., 2017). Surface mineralogy could also be measured using in situ visible-mid-IR spectroscopy, X-ray diffraction, and Raman Spectroscopy, while Mössbauer spectroscopy could measure oxidation state. Measurements of the near-surface atmosphere would also inform the state of surface-atmosphere equilibrium.

3.2.3.3. Investigation III.B.CI. Chemical Interactions (Targeted): It is important to determine the abundances of crucial species (e.g. CO, OCS, SO_2) in the lowest atmospheric scale height, where surface-atmosphere interactions occur (Gilmore et al., 2017; Zolotov, 2018). Inferences about their near-surface concentrations have previously been made through extrapolation of their observed higher elevation concentrations (e.g., Arney et al. 2014) and through model predictions (e.g., Fegley and Treiman 1992), which also suggest several possible atmospheric reaction products. Because the average Venus atmosphere is oxidized compared to basaltic rock, surface chemistry should produce reduced gas species, like CO from CO_2, and SO_2 or S_2 from SO_3. Oxygen fugacity (fO_2) is also directly linked to surface equilibrium chemistry through these variables and is poorly constrained for Venus. Data from Venera landing sites indicate that some Venusian surface materials may be enriched in S relative to Earth basalts, suggesting processes of sulfur-based basaltic weathering. SO_3 in the atmosphere may react with Ca-bearing silicates to form $CaSO_4$ (anhydrite) thus reducing the proportion of atmospheric sulfate (Barsukov et al., 1982). Atmospheric halogens could exchange with the surface, perhaps reducing the Cl/F ratio by formation of Cl-bearing phosphate phases. If Venus' volcanic rocks include hydroxy-bearing igneous minerals (such as amphibole or biotite), then their decomposition should release hydrogen (with D/H values of the interior) to the atmosphere.

In-situ direct measurements of the deep Venus atmosphere would provide clarity to questions of the concentrations and distributions of gases whose lowest scale height concentrations have only been inferred. This Investigation could be accomplished via landers or descent probes with suitably designed mass spectrometers. Determining gradients on a regional scale would be enabled by orbital or aerial platforms carrying high-spectral-resolution spectrometers. Interpretation of these deep atmosphere spectra would be improved by better laboratory and/or theoretical estimates of the effects of pressure broadening on the specific line widths and strengths relevant to the Venus lower atmosphere. Experiments at the relevant temperature and pressure of the Venusian surface could answer questions of which surface-atmosphere chemical reactions are plausible explanations for observed gas concentrations.

4.0. Conclusions

Many fundamental questions about the origin and evolution of Venus await answers. Venus could have maintained a habitable environment with liquid water oceans for billions of years, and detectable signatures of this ancient epoch could await discovery by new missions. The rapid rate of ongoing discoveries of Venus-sized exoplanets makes unveiling Venus especially pressing, given that many more exoplanets may soon be amenable to atmospheric characterization. After a year-long process featuring a plethora of forums for community feedback, VEXAG has prepared this report centered on three Goals, six Objectives, and 23 Investigations that could drive a sustained program of Venus exploration. Dramatic advances in our scientific understanding of Venus and other terrestrial planets are achievable within the next few decades if we can muster the collective will to explore Venus.

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Appendix A: Future Investigations

All Investigations in Table 1 were judged to have very high scientific merit along with feasibility in terms of technology and mission opportunities within the designated time period of these reports (i.e., within a few decades). Thus, this report does not include potential Investigations that may have very high scientific merit but relatively low feasibility. In particular, two Investigations were considered but judged to require resources substantially beyond the Flagship mission class and/or technology development outside the scope of these reports. We provide their descriptions as examples of the types of science that would be become achievable beyond the next decade after a program of Venus exploration has advanced:

<u>Example Investigation III.A.AA. Absolute Ages</u>

In the absolute sense, nothing is known about the surface age of rocks on Venus' surface. Although impact ages suggest the surface may be quite young (McKinnon et al., 1997), the possibility remains that some units might date from a time when Venus was habitable (Gilmore et al., 2017; Hansen and Lopez, 2010). Technology for in situ age dating is rapidly evolving, as evidenced by the success of the Sample Analyzer at Mars (SAM) instrument on Mars Science Laboratory. A long-term goal of the Venus Exploration Program is to obtain analogous in situ measurements of multiple locations on the surface. Current technology in development for this purpose includes SAM-like instruments and other solutions using high resolution Laser induced breakdown Spectroscopy (LIBS). The latter method measures the emission spectra of molecules and molecular ions, enabling identification of specific isotopes within the plasma plume. Because sample preparation is not needed, LIBS provides a viable solution for Venus exploration.

<u>Example Investigation I.B.DS. Deep Structure</u>

Decades of study have revealed heterogeneous structure within Earth such as mantle plumes, laterally varying depths of seismic velocity discontinuities associated with mantle phase transitions, large low shear velocity provinces, and ultra-low velocity zones in the mantle (e.g., French and Romanowicz 2015; Hernlund and McNamara 2015). Seismology has also revealed hints of slow layers at the top and bottom of the liquid, outer core (e.g., Adam and Romanowicz 2015; Garnero et al. 1993). This structure reflects thermal and/or compositional variations that constrain planetary accretion, differentiation, and ongoing processes. Considerable investment and technological development would be required to return Earth-quality seismic data from Venus. However, many signatures of important dynamical processes are likely buried in the deep interior. Excitingly, True Polar Wander (TPW) may occur quite rapidly on Venus relative to Earth and Mars because the equatorial bulge in the solid body is tiny and provides little obstacle to rotational realignment. Mantle convection (or, more detectable, large volcanic eruptions) could provide enough mass redistribution to provoke an episode of TPW.

Orbiter missions that conduct radar imaging with long temporal baseline could track the motion of surface features associated with TPW (e.g., at rates of ~1 m per year). Obtaining detailed constraints on plume structure, mantle seismic discontinuities, and chemical stratification in the lower mantle and core would require a global network of long-lived surface platforms.

Appendix B: Linking the 2019 and 2016 VEXAG GOI Documents

The following table illustrates the connections between the Investigations in this document and previous versions. Overall, items in the GOI have been reworded and reorganized but the overall scientific content remains mostly unchanged. Removing the relative prioritization of Objectives and Investigations is perhaps the most impactful difference between this document and previous versions. Because so many pressing questions about Venus await answers, it is accurate to describe multiple Investigations as having the highest level of scientific priority.

Table A2.1. Investigations in the 2019 and 2016 VEXAG GOI

Note that Objectives and Investigations were prioritized in the 2016 GOI. Investigations in the 2019 GOI are categorized but not prioritized within each category. For example, Investigations I.A.HO. and I.B.IS. have equal (highest) priority in this 2019 GOI.

Investigation in 2019 GOI	Related Investigation(s) in 2016 GOI
I.A.HO. Hydrous Origins (1)	III.A.2. III.A.3.
I.A.RE. Recycling (1)	II.A.3.
I.A.AL. Atmospheric Losses (2)	I.A.2.
I.A.MA. Magnetism (3)	II.A.3.
I.B.IS. Isotopes (1)	I.A.1. I.A.2. II.A.2. III.A.1. III.B.1. III.B.4.
I.B.LI. Lithosphere (1)	II.A.3.
I.B.HF. Heat Flow (2)	
I.B.CO. Core (2)	II.B.4.
II.A.DD. Deep Dynamics (1)	I.B.1. I.B.3. I.C.1.
II.A.UD. Upper Dynamics (1)	I.B.1. I.B.3.
II.A.MP. Mesoscale Processes (2)	I.B.1. I.B.3. I.C.1.
II.B.RB. Radiative Balance (1)	I.B.2.
II.B.IN. Interactions (1)	I.C.1.
II.B.AE. Aerosols (2)	I.C.1. I.C.2. I.C.3.
II.B.UA. Unknown Absorber (2)	I.C.2. I.C.4.
II.B.OG. Outgassing (3)	III.B.4.
III.A.GH. Geologic History (1)	II.A.1. II.B.6.

III.A.GC. Geochemistry (1)	II.B.1. II.B.2. II.B.5.
III.A.GA. Geologic Activity (2)	II.A.4.
III.A.CR. Crust (2)	II.B.3. II.B.6.
III.B.LW. Local Weathering (1)	III.B.2.
III.B.GW. Global Weathering (2)	III.B.2.
III.B.CI. Chemical Interactions (3)	III.B.3.

Appendix C: Linking the 2019 VEXAG GOI and Roadmap

The VEXAG "Roadmap for Venus Exploration" describes a program of Venus exploration featuring twelve mission modalities. The following tables define each modality and indicate those that are potentially useful to each Investigation. Because the VEXAG GOI is not designed to prescribe particular missions, the omnibus table is only intended as a general guide.

Table C.1

Platform Type/ Subtype Time Frame	**Description of platform and primary scientific objectives**
ORBITER	**Supports Investigations from orbital vantage points optimized for the scientific objectives**
Surface/Interior Near-term	Single spacecraft in a circular, low altitude, near polar orbit optimized for most Investigations of the surface and interior including those involving radar imaging and topography, infrared mapping, and gravity.
Atmosphere/Ionosphere Near-term	Single spacecraft in an eccentric, long-period orbit optimized for atmospheric remote sensing (e.g., nadir and limb viewing) and in situ sensors of the ionosphere and induced magnetosphere.
SmallSat or CubeSat Near-term	Single or multiple spacecraft focused on highly targeted Investigations requiring tailored orbits. May also provide relay, navigation support, and synergistic science for surface and aerial platform(s).
ATMOSPHERIC ENTRY	**Supports experiments during a traverse or descent in the Venus atmosphere**
Skimmer Near-term	Skims the atmosphere, sampling the Venus atmosphere at a very high altitude and emerging from the atmosphere for sample analysis and data relay.
Probe Near-term	Enters the atmosphere and descends to the surface but not designed to operate after impact. Would investigate atmospheric structure and compositions along a single profile as well as near-surface imaging.
Sonde Mid-term	Deploys from an aerial platform that is already at the operational altitude. Sonde relays data through the aerial platform as it descends. Advanced versions could target surface features.
SURFACE PLATFORM	**Supports experiments on the surface of Venus in the high temperature high pressure environments**
Short-Lived Near-term	Classic (e.g., Venera) lander capable of surviving on the surface for several hours. Various instruments could investigate elemental and mineral compositions of nearby rocks, including variations with depth.
Long-Lived, Pathfinder Mid-term	Designed to operate for at least one Venus solar day (≥117 Earth days) on the surface. Measurements include temperature, wind velocity, and chemistry of major species and possibly demonstration of a seismic sensor.
Long-Lived, Advanced Far-term	Capable of both short duration (one Earth day) Investigations of the surface and longer-term Investigations of the atmosphere, heat flow and seismicity of the planet through at least two Venus solar days.

AERIAL PLATFORM	**Supports extended duration experiments in and from the atmosphere including sonde deployment**
Fixed Altitude – Mid Cloud Near-term	Floats at a nominal altitude of ~55 km in day and/or night at temperature near 20 °C. Carried around the planet in six days by the RZS and conducting Investigations of the atmosphere and interior.
Variable Altitude – Mid Cloud Mid-term	Controls altitude in the range ~50–60 km enabling compositional and structural Investigations of different regions within the clouds enhancing the range of Investigations of the atmosphere and interior.
Variable Altitude – Cloud Base Far-term	Controls altitude in the range ~40–60 km using passive thermal control systems to enable use of conventional electronics. Sensors in exposed locations must tolerate temperatures up to 150 °C.
FLYBY OPPORTUNITIES	**Opportunistic leveraging of non-Venus missions for Venus science of multiple possible types, depending on the opportunity**

*In keeping with other Venus guidance documents, ‘Near-term’ here refers to the 2020-2022 timeframe, ‘Mid-term’ to 2023-2032, and ’Far-term’ to 2033-2042.

Table C.2 Mapping of GOI to Venus Roadmap

VEXAG GOI			Roadmap Mission Modalities											
Goal	Objective	Investigation	Orbiter	Orbiter	Orbiter	Atmospheric Entry			Surface Platform			Aerial Platform		
			Surface/ Interior	Atmosphere	SmallSat	Skimmer	Probe	Sonde	Short-lived	Long-lived (Pathfinder)	Long-lived (Advanced)	Fixed Altitude	Variable Altitude	Variable+ Altitude
			Near-term	Near-term	Near-term	Near-term	Near-term	Mid-term	Near-term	Mid-term	Far-term	Near-term	Mid-term	Far-term
I. Early evolution and potential habitability	Did Venus have liquid water?	I.A.HO. (1)	Vital	Supporting	Supporting				Vital		Vital			Vital
		I.A.RE. (1)	Vital						Vital		Vital	Supporting	Supporting	Supporting
		I.A.AL. (2)		Vital	Vital									
		I.A.MA. (3)		Supporting	Supporting				Supporting	Supporting	Supporting	Vital	Vital	Vital
	How does Venus inform pathways for planets?	I.B.IS. (1)				Vital	Vital	Vital	Vital		Vital	Vital	Vital	Vital
		I.B.LI. (1)	Vital	Supporting	Supporting					Supporting	Vital	Vital	Vital	Vital
		I.B.HF. (2)	Vital								Vital			
		I.B.CO. (2)	Vital		Supporting					Supporting	Vital			
II. Atmospheric dynamics and composition	What drives global dynamics?	II.A.DD. (1)		Vital	Vital		Supporting	Supporting		Vital	Vital	Supporting	Vital	Vital
		II.A.UD. (1)		Vital	Vital	Supporting								
		II.A.MP. (2)		Vital	Supporting		Supporting	Supporting				Supporting	Vital	Vital
	What governs composition and radiative balance?	II.B.RB. (1)		Vital	Vital		Supporting	Supporting	Supporting	Vital	Vital	Supporting	Vital	Vital
		II.B.IN. (1)		Vital	Supporting		Vital	(light blue)		Supporting	Supporting	Supporting	Vital	Vital
		II.B.AE. (2)		Supporting	Supporting		Vital	Vital	Supporting	Supporting	Supporting	Vital	Vital	Vital
		II.B.UA. (2)		Vital	Vital		Supporting	Supporting				Supporting	Vital	Vital
		II.B.OG. (3)	Vital	Vital	Vital		Supporting	Supporting	Supporting	Supporting	Vital	Supporting	Vital	Vital
III. Geologic history and processes	What geologic processes shape the surface?	III.A.GH. (1)	Vital	Vital	Vital									Supporting
		III.A.GC. (1)	Supporting	Supporting	Supporting		Supporting	Supporting	Vital	Vital	Vital			Vital
		III.A.GA. (2)	Vital	Supporting	Supporting		Supporting	Supporting		Supporting	Vital	Supporting	Supporting	Supporting
		III.A.CR. (2)	Vital	Supporting	Supporting					Supporting	Vital	Vital	Vital	Vital
	Atmosphere and surface interactions?	III.B.LW. (1)	Supporting	Vital	Vital		Vital	Vital	Vital	Vital	Vital			Supporting
		III.B.GW. (2)	Vital	Vital	Vital				Supporting	Supporting	Supporting	Supporting	Supporting	Vital
		III.B.CI. (3)	Supporting	Supporting	Supporting		Vital	Vital	Vital	Vital	Vital	Supporting	Supporting	Vital

Color Code	Meaning
Vital	**Vital:** Mission modality enables measurements that are vital (either alone or in combination) to completing the investigation.
Supporting	**Supporting:** Mission modality enables measurements that substantially contribute to completing the investigation.