Goals, Objectives, and Investigations for Venus Exploration

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Venus Exploration
VEXAG
Analysis Group

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At the VEXAG meeting in November 2017, it was resolved to update the scientific priorities and strategies for Venus exploration. Here, we present the Goals, Objectives and Investigations for Venus Exploration.

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1. Introduction

Venus and Earth are often described as twins. Their sizes and densities are nearly identical, and they are much larger than other terrestrial planetary bodies. 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 identify planetary systems beyond our Solar System (e.g., the Kepler mission and the Transiting Exoplanet Survey Satellite) are ultimately aimed at finding Earth-size planets in the "habitable zone" of their parent stars. The Venus-Earth comparison will be critical in assessing the likelihood that Earth-size means Earth-like for these discoveries.

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), Venus was listed as an "important object of study" in all three crosscutting themes:

- Building new worlds—understanding solar system beginnings,
- Planetary habitats—searching for the requirements for life, and
- Workings of solar systems—revealing planetary processes through time.

The decadal committee recommended the Venus In Situ Explorer as one of seven candidate New Frontiers Missions 4 and 5 and the Venus Climate Mission as one of five candidate flagship missions. Recently, the midterm review of NASA's progress at meeting the objectives of the decadal survey noted that exciting Venus research has continued since the decadal survey. In particular, the VIRTIS instrument on Venus Express provided tantalizing evidence that the tesserae terrains are felsic—suggesting that they formed in the presence of a large amount of water. Laboratory simulations show that sites of plume-induced subduction on Venus could serve as an analog for early Earth when plate tectonics first began. The JAXA Akatsuki mission 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. Overall, the midterm review issued a finding that programmatic balance in selected missions is vital to achieving comparative planetology investigations recommended by the decadal survey.

Through an extended process including input from the community at town hall meetings, VEXAG has developed this list of scientific Goals, Objectives, and Investigations to both serve the priorities of the latest decadal survey and motivate future community efforts. In particular, NASA's future exploration of Venus should strive to achieve three non-prioritized Goals:

I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-sized (exo)planets,
II. Understand atmospheric composition and dynamics on Venus, and
III. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

These Goals and their associated Objectives and Investigations are listed in Table 1. Objectives, like Goals, are <u>not</u> prioritized. This is because developing an understanding of Venus as a system requires making progress in each of these scientific areas. Every Investigation was judged to provide high scientific value; investigations of lower priority were omitted from Table 1 entirely.

Investigations are categorized as either Essential (1), Important (2), Targeted (3), or Future (4) based on their relationship to the overarching objective. Investigations in categories 1–3 were judged as technically feasible within the scope of the VEXAG Roadmap for Venus Exploration. Completing all Essential (1) Investigations essentially fulfills the Objective. Important (2) Investigations address many aspects of the Objective and provide valuable context for other Investigations. Targeted (3) Investigations address particular aspects of an Objective that significantly contribute to our overall understanding of Venus. Investigations labeled as Future (4) were judged to require investment above the flagship class and/or major development of technology before becoming feasible, although their scientific impacts should merit the necessary work. Crucially, Investigations are not prioritized in any way within each category.

Neither the terse wording in Table 1 nor the discussions in the text are intended to be literally prescriptive. Designers of future missions should have the latitude to design platforms and instruments to best achieve the scientific priorities expressed in this document and the decadal survey. Because Venus is a complex, relatively unexplored planet, no one mission below the flagship class could possibly complete all of the high-priority science identified by the scientific community. Ultimately, a sustained program of Venus exploration would unveil the workings of Earth's nearest neighbor with broad implications for our Solar System and beyond.

<table>
<tr><th colspan="3">Table 1. VEXAG Goals, Objectives, and Investigations</th></tr>
<tr><td colspan="3">Goals and Objectives are not prioritized. Investigations are categorized as Essential (1), Important (2), Targeted (3), or Future (4) but are not prioritized within each category.</td></tr>
<tr><th>Goal</th><th>Objective</th><th>Investigation</th></tr>
<tr><td rowspan="9">I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.</td><td rowspan="4">A. Did Venus have temperate surface conditions and liquid water at early times before transitioning into a runaway greenhouse?</td><td>1. Hydrous origins. Determine whether Venus shows evidence for abundant silicic igneous rocks and/or ancient sedimentary rocks.</td></tr>
<tr><td>1. Recycling. Search for structural, geomorphic, and chemical evidence of crustal recycling on Venus.</td></tr>
<tr><td>2. Atmospheric losses. Quantify the processes by which the atmosphere of Venus loses mass to space, including interactions between magnetic fields and incident ions and electrons.</td></tr>
<tr><td>3. Magnetism. Characterize the distribution of any remanent magnetism in the crust of Venus.</td></tr>
<tr><td rowspan="5">B. How does Venus elucidate possible pathways for planetary evolution in general?</td><td>1. Isotopes. Measure the isotopic ratios and abundances of D/H, noble gases, oxygen, nitrogen, and other elements in the atmosphere of Venus.</td></tr>
<tr><td>1. Lithosphere. Determine physical parameters that may control transitions between global tectonic regimes on Venus, including: rheology, stress state, and the thermal and physical states of the lithosphere.</td></tr>
<tr><td>2. Heat flow. Characterize crustal heat flow, dynamic compensation, and elastic and mechanical thicknesses across the surface of Venus.</td></tr>
<tr><td>2. Core. Measure the size of the core of Venus and determine whether it remains partially liquid.</td></tr>
<tr><td>4. Deep structure. Search for chemical heterogeneity in the core and lower mantle as ancient remnants of accretion and differentiation.</td></tr>
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Table 1 (continued). VEXAG Goals, Objectives, and Investigations		
II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus?	**1. Deep dynamics.** 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.
		1. Upper dynamics. In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.
		2. Mesoscale processes. 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?	**1. Radiative balance.** Characterize atmospheric radiative balance and how radiative transport drives atmospheric dynamics on Venus.
		1. Interactions. Characterize the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere.
		2. Aerosols. Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.
		2. Unknown absorber. Characterize the unknown short-wavelength absorber in the upper atmosphere of Venus and its influence on local and global processes.
		3. Outgassing. Determine the products of volcanic outgassing on Venus and their effects on atmospheric composition.
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?	**1. Geologic history.** Develop a geologic history for Venus by characterizing the stratigraphy, modification state, and relative ages of surface units.
		1. Geochemistry. Determine elemental chemistry, mineralogy, and rock types at localities representative of global geologic units on Venus.
		2. Geologic activity. Characterize current volcanic, tectonic, and sedimentary activity that modifies geologic units and impact craters and ejecta on Venus.
		2. Crust. Determine the structure of the crust of Venus in three dimensions and thickness across the surface.
		4. Absolute ages. Determine absolute (radiometric) ages for Venus rocks at locations that are key to understanding the planet's geologic history.
	B. How do the atmosphere and surface of Venus interact?	**1. Local weathering.** Evaluate the mineralogy, oxidation state, and changes in chemistry of surface-weathered rock exteriors at localities representative of global geologic units on Venus.
		2. Global weathering. Determine the causes and spatial extents of global weathering regimes on Venus.
		3. Chemical interactions. Characterize atmospheric composition and chemical gradients from the surface to the cloud base both at key locations and globally.

2. Descriptions of Goals, Objectives, and Investigations

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

It is currently unknown whether Venus and Earth both hosted liquid water oceans for billions of years, or whether these celestial cousins trod distinct evolutionary paths from the birth of the Solar System. Unveiling Venus is especially important given ongoing interest in terrestrial exoplanets, which are now being detected at a rapid rate with current and future exoplanet-related missions aiming to characterize the atmospheres of these planets. 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 prevalence of Venus analogs is especially relevant given that the *Transiting Exoplanet Survey Satellite (TESS)* mission is expected to detect hundreds of terrestrial planets orbiting bright host stars. The discoveries of *TESS* will provide key opportunities for transmission spectroscopy follow-up observations using the *James Webb Space Telescope (JWST)*, amongst other facilities.

Objective I.A. | Did Venus have temperate surface conditions and liquid water at early times before transitioning into a runaway greenhouse?

Answering this question requires searching for rocks on the surface that formed in the presence of large amounts of liquid water [I.A.1. Hydrous Origins]. If geologic evidence for ancient oceans is found, then understanding mechanisms of volatile loss becomes extremely important. Possible mechanisms include recycling into the interior [I.A.1. Crustal Recycling] and/or loss to space [I.A.2. Atmospheric Losses]. Searching for evidence of an ancient dynamo [I.A.3. Magnetism] is highlighted as a Targeted Investigation because any detection of crustal remanence would place an upper limit on recent surface temperatures and constrain models of atmospheric interaction with the solar wind.

<u>Investigation I.A.1. Hydrous Origins</u>

This Investigation (and implied measurements) is considered Essential because of the importance of water, especially as a liquid, to understanding Venus' geological evolution and its past potential for habitability. Several types of measurements can be used to address this Investigation: remote measurement of VNIR emittance; radar with high spatial resolution, and chemical analyses of surface material.

The presence or absence of liquid water in Venus' early history is crucial to understanding Venus' evolution in comparison to other planets, water-bearing (Earth, Mars) or not (Mercury, the Moon). Although liquid water is not now present, some types of rock require water to form. A prime example would be abundant granitic rock, as has been suggested for some tesserae. On Earth, the abundant granitic rock of its continents was only possible because water was relatively abundant in the crust and mantle where magmas were being generated. Similarly, some sedimentary rock types cannot form without liquid water, such as those rich in minerals like: sulfate and halide (evaporite), silica (hot springs or 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).

These questions can be addressed, in different ways, by remote sensing (orbit or balloon), and by in situ analyses. Many granitic rock types have much lower VNIR emissivities than basaltic rocks, and these different signatures can be accessed through several spectral 'windows' (near 1 μm) in Venus' thick atmosphere. Similarly, sediments rich in evaporites, silica, or carbonate, should have low emissivities and be distinct. Emissivities could be measured from orbit, from balloons, or from the surface. The physical characteristics of clastic sedimentary systems may be discernable from orbital or balloon radar, given high-enough spatial resolution. Landers are required to provide the most detailed determinations of rock type and physical inter-relationships using high-resolution imagers and chemical analysis instruments (such as x-ray fluorescence, gamma ray spectrometry, or LIBS). Lander instruments may remove any surface rind from chemical weathering to measure the intrinsic composition of the rock.

Investigation I.A.1. Crustal Recycling

Crustal recycling is the phenomenon whereby surface and near-surface material is introduced by subduction and/or delamination to the planetary interior, where it can participate in melt production and the chemical evolution of the lower crust and mantle. The identification of widespread ongoing or ancient crustal recycling on Venus would have profound implications for our understanding of the thermal, chemical, geological, and atmospheric evolution of the planet, and of terrestrial planets in general. Localized plume-induced subduction has been proposed to operate on Venus, and there is evidence of substantial lateral mobility of some parts of the crust. Moreover, crustal recycling is predicted to result in lavas with distinctive geochemical signatures, and numerous regions of tesserae on Venus have been hypothesized to correspond to continental-like material formed during an earlier era of crustal recycling. However, currently available 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. Nonetheless, full global radar image and topographic data, from an orbital platform, at resolutions substantially higher than those from Magellan could help search for geomorphological evidence of crustal recycling (including, but not limited to, subduction trenches and locally elevated, fault-bound terrain)—especially if coupled with yet higher-resolution targeted image and topographic observations and/or high-resolution gravity field data. In situ measurements by a landed platform of lava flows could test for chemical evidence for recycling (e.g., enrichment or depletion of incompatible elements such as Nb, Zr, rare-earth elements, etc.). Similarly, direct chemical analyses of tessera terrain would provide a test of that material corresponding to Earth-like continental crust (e.g., by assessing Si abundance). Finally, crustal recycling on Earth is frequently associated with quake events. The detection from an orbital, atmospheric, and/or surface platform of seismic activity on Venus would contribute to our overall understanding of the physical and chemical properties of the lithosphere, in turn placing better estimates on the likelihood of crustal recycling having ever operated there.

Investigation I.A.2. Atmospheric Losses

Atmospheric loss processes on Venus are critically important to the evolution of its atmosphere. The high D/H ratio (150 times that of Earth's oceans) implies that Venus might once have held an ocean's worth of water but, somehow, lost most of it to space. As Venus only has an induced magnetic field, the solar wind is able to penetrate deep into the ionosphere, causing intense atmospheric erosion.

Venus' escape velocity is 10.4 km/s which, unlike Mars, is too great for atmospheric escape to be driven by thermal or photochemical processes at present day. Therefore, nonthermal escape driven by the solar wind is *the most important* process in the loss of Venus' atmosphere. As such, the study of the solar wind and how it interacts with the Venusian upper atmosphere, both during solar minimum and solar maximum, are imperative in understanding Venus' atmospheric escape and evolution.

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. 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 is always present via ambipolar diffusion, a process which is much more efficient at Venus than any other terrestrial planet. Added to this is the fact that the Sun experienced more frequent and intense activity while it was young, having an even greater impact on early atmospheric evolution.

While loss processes have been addressed by PVO and VEX, they are not necessarily well characterized. Observations of both the upstream solar wind and the Venusian atmosphere during solar minimum and maximum are needed in order to build a more complete study of atmospheric erosion. Measurements of study solar wind interaction with Venus are many and varied. Instruments needed to study the Venusian atmosphere and the solar wind include, but are not limited to, electron spectrometers, ion mass spectrometers, neutral particle detectors, UV and visible spectrographs and imagers, SEP detectors, Langmuir probes, and magnetometers. These types of studies are best conducted with orbiting spacecraft (possibly including networks of CubeSats and/or SmallSats), ideally in an orbit which samples both the solar wind environment (to establish upstream solar wind conditions) and the plasma environment.

<u>Investigation I.A.3. Magnetism</u>

Venus has no intrinsic magnetism today but may have hosted a dynamo in the past because its rotation is fast enough that the Coriolis force would have a large effect on flow in its conductive, metallic core. Detecting any crustal remanent magnetism would place unique constraints on planetary accretion, geologic processes, and climate history. For example, simulations predict a dynamo operated within the average surface if the core of Venus was initially “Earth-like,” meaning hot and chemically homogeneous. Near-surface temperatures could have remained >100 K below the Curie points of common magnetic minerals such as magnetite and hematite that may retain thermoremanent magnetization for billions of years. Measurements from Pioneer Venus Orbiter and Venus Express only rule out crustal magnetic fields with strong magnetizations and coherence wavelengths >150 km northwards of 50° South latitude. Venera 4 landed in Eistla Regio and also failed to detect any crustal remanence.

Future orbiters could still detect strong, large-scale crustal fields southward of 50° South latitude. Relatively weak, large-scale fields and/or strong, localized fields could exist anywhere on the surface except the Venera 4 landing site. Magnetometer measurements at low altitudes such as from an aerial platform are vital because magnetic field power decreases rapidly (e.g., as distance cubed) at altitudes above the coherence wavelength of the source magnetization.

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 await discovery with new telescopes. No general model for the long-term evolution of terrestrial exoplanets can rest on a foundation of fundamental ignorance about Earth and Venus.

Investigation I.B.1. Isotopes

This Investigation is considered Essential because the isotopic composition of Venus' atmosphere should preserve significant clues to Venus' early history, accretion and differentiation. Instrumentation of high TRL is available to address this investigation, and it can be implemented in a wide range of spacecraft platforms.

Foremost among atmospheric constraints is the deuterium/hydrogen ratio, D/H, which is known to be extremely high, approximately 100 times that on the Earth (with significant uncertainties). The high D/H is interpreted as a result of massive loss of H to space, and thus that Venus once had enough hydrogen to allow significant bodies of liquid water (see IA 1. Ancient water). If so, it is possible that Venus once hosted habitable environments, and possibly life. However, uncertainty in the D/H value allow several scenarios for early Venus.

The nature of Venus' early volatiles, sources and compositions, can be addressed by constraints on other elements in its atmosphere, including N, C, Cl, and the heavy noble gases. The isotopic compositions of these gases will help define the sources of Venus' volatiles (e.g. cometary versus asteroidal), whether they were affected by atmosphere loss processes (see IA 2. Atmospheric Losses), the extent of outgassing from the solid planet (see IIB 3. Outgassing), and whether biology may now be active (see IIB 1. Interactions). Xenon is of particular importance for understanding Venus' origin, because the terrestrial planets appear to have tapped distinct sources of it; it is also possible that Xe has been depleted from the Venus atmosphere in the same processes that produced the high D/H ratio. Radioactive decay of ^{40}K produces ^{40}Ar, and thus measurements of atmospheric ^{40}Ar constrain the rate of volcanic outgassing from the interior.

This Investigation is most directly addressed by mass spectrometry, placing such an instrument in the Venus atmosphere. The most useful analyses would be from depths in the atmosphere where it is well-mixed, deeper than the homopause. Mass spectrometers have been deployed on probe and lander spacecraft (like the Pioneer Venus probe, and Venera/VEGA), with varying success. These platforms remain suitable, as would an aerial platform or atmospheric skimmer, for deploying a mass spectrometer.

Investigation I.B.1. Lithosphere

This Investigation is considered Essential because the lithosphere influences the convection regime of Venus and links interior activity with surface observables. Venus shows no evidence for a global regime of plate tectonics similar to that observed on Earth, implying that the lithosphere is either too strong to be mobilized by mantle convection or that its rheology is not able to sustain localized deformation over long spatial and temporal scales. The current dynamical regime of Venus, whether it involves stagnant-lid convection, heat pipes, episodic plate tectonics, or another mode of mantle convection remains poorly understood. Studying the lithosphere requires combining the observational constraints described above with geodynamic models to characterize the long-term thermal and chemical evolution and potential habitability.

High-resolution gravity maps, combined with much improved electromagnetic sounding, altimetry and high-resolution radar imagery, would provide new understanding of lithosphere of Venus. This data could be obtained by a GRAIL-like mission in orbit and global high-resolution stereo SAR imagery collected from an orbital or aerial platform. Gravity and topography would reveal topographic support processes over a variety of scales. Along with analyses of stress state, local flexure, and quantitative analyses of faulting and volcanism, this information would constrain the lithosphere-scale rheology. Inductive electromagnetic sounding of the crust and upper mantle would use global resonances below the ionosphere caused by lightning and therefore must be performed from the surface or an aerial platform. Combined with compositional information, inferred from the radar characteristics of the surface, spectroscopic measurement, *in situ* chemical analyses where available, and gravity inversion, the rheology of the lithosphere would pose new constraints on the variations of temperature with depth, and how if varies geographically, revealing in unprecedented detail the ways that heat and volatiles are transferred through the lithosphere. This knowledge would then inform long-term interior and atmosphere evolution models, addressing the potential for ancient habitability of the planet.

<u>Investigation I.B.2. Heat Flow</u>

The Magellan mission provides all available constraints on the lithosphere and heat flow. The wavelength of elastic lithospheric bending is determined by its thickness, which is a function of its composition and temperature. The elastic thickness and thus temperature (assuming composition) of the lithosphere can be constrained from both modeling of flexural bending observed in the topography, from modeling admittance (the ratio of gravity and topography in the spectral domain), as well as modeling of surface deformation in limited loading environments, such as large volcanos. Existing estimates of elastic thickness from gravity data often have large uncertainties due to the limited accuracy and resolution of the present gravity field. Values from modeling topographic bending are better constrained but are limited to small subset of volcanoes and coronae where flexure can be observed. A further significant limitation is the unknown relative age of the surface. On other terrestrial planets, thermal evolution with time can be evaluated using impact craters to estimate the age of regions with a given elastic thickness. On Venus the limited ability to estimate relative age is hampered by low-resolution imaging and topography that cannot determine unequivocally whether impact craters are volcanically flooded or modified by aeolian processes. Some workers argue that many impacts are flooded, implying a young average surface. However, such studies are conducted using the spatially limited stereo topography, which is arguably at the limit of the required resolution.

Heat flow estimation can be very significantly improved from orbit by measuring high resolution topography to look for lithospheric flexure at smaller scale features, such as at the hundreds of volcanoes, and by improving the resolution of the gravity field such that well constrained values of elastic thickness can be determined. The highest quality measurement of heat flow in targeted locations would come in-situ measurements. Such measurements would need to be coupled with that of surface brightness temperature to remove the seasonal/daily temperature variation. An improved understanding of relative age requires both high resolution topography and imaging to assess modification of impact craters and their extended ejecta.

<u>Investigation I.B.2. Core</u>

The size and physical state of the core is a key constraint on models of the thermal evolution of Venus. Energy from giant impacts (kinetic) or rapid accretion (gravitational) is expected to completely melt the core as an initial condition. 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. Two basic measurements of Venus are missing: total moment of inertia and radius of the core.

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.

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. Ground-based instruments such as the 70 m antenna at Goldstone, CA and the 100-m telescope at Green Bank, WV are capable of measuring the instantaneous length of day and, over time, estimates of the spin precession rate that are directly related to the polar moment of inertia. As planned for the NASA InSight mission on Mars, a single seismological station is potentially capable of measuring the radius of the core.

Investigation I.B.4. Deep Structure

Decades of study has 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. Seismology has also revealed hints of slow layers at the top and bottom of the liquid, outer core. 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 surface platforms.

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

The study of a planetary atmosphere is essentially the characterization of a planet-scale four-dimensional heat engine. Energy deposition depends strongly on the stellar (solar) inputs and the planetary response to those inputs. The amount of energy absorbed as a function of altitude, latitude, and solar time, and the efficiency with which that energy is distributed throughout the planet are key factors in determining the habitability of a planet. Collection of sufficient data to answer all of the key questions of atmospheric composition, dynamics, and evolution would require a fleet of in situ and orbital platforms capable of building the complete four-dimensional picture. The case of Earth is a good example, exhibiting thousands of ground stations, hundreds of semidiuirnal atmospheric profiles via radiosonde, and dozens of satellites dedicated to measuring key constituents and parameters and providing global context. In order to pursue these same questions in an extraterrestrial sense (for example, the planet Venus), it is helpful to break them down into semi-independent regional questions, while still recognizing that these processes are not decoupled. The ultimate goal remains to understand how all of the various processes are interconnected as a coherent planetary system; specifically, what is the primary driver of an atmosphere such as that of Venus, and how has it arrived at its present state?

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

Perhaps the most obvious physical characteristics of Venus are its global cloud cover and the atmosphere's retrograde zonal super-rotation (RZS). Current understanding is that the winds on Venus flow primarily from east to west at almost all altitudes below about 85 km [II.A: Lower Dynamics]. Near the surface, the wind speed is a pedestrian few m/s; but the high density of the 92-bar surface pressure means that these slow winds exert a dynamic pressure that is equivalent to those exerted by a Gale Force wind (17.5–24.2 m/s) at the surface of the Earth. The wind speeds increase with altitude, reaching a peak in angular momentum at an altitude of about 20 km, and a peak in magnitude at an altitude of around 75 km, just above the cloud tops. Above this altitude, in a region sometimes called the "ignorosphere" due to the difficulties involved in studying it, the winds transition to a subsolar to antisolar (SSAS) flow, before transitioning back to a zonal super-rotation in the upper thermosphere. Recent analysis of airglow variability seen in Venus Express data demonstrates that aeronomy and solar-atmosphere interactions play a role in driving the dynamics of the upper atmosphere of Venus [II.A: Upper Dynamics].

A global-scale wave discovered by Akatsuki's Longwave Infrared camera and also found in Akatsuki's UV Imager data is tied to the surface topography, and exhibits regular time-of-day recurrence. This has demonstrated the importance of surface-atmosphere interactions at Venus, and the role of solar-atmosphere interactions, even in the deep atmosphere [II.A: Lower Dynamics]. The coupling of this near-surface phenomenon to observed behavior near the cloud tops indicates the significance of modulation of vertical propagation of energy and momentum via convection and wave activity [II.A: Mesoscale Processes]. Is the super-rotation driven primarily from above or from below? More likely, it is a combination of both. What is the magnitude of the surface-atmosphere interaction on the Venus atmospheric super-rotation; and what effect does this have on the solid body rotation [I.B: Core]? To what extent do thermal tides and solar-atmospheric interactions that drive the SSAS flow contribute to or counter the atmospheric super-rotation [II.A: Upper Dynamics]? How effective are the vertical propagation of energy and momentum via waves at a variety of scales, and via convective processes [II.A: Mesoscale Processes]? In order to answer this these questions about Venus atmospheric dynamics, an accumulation of data covering a wide range of altitudes, latitudes, local solar time, geographical area, and with good temporal coverage, both in cadence and extent, are required.

Investigation II.A.1. Deep Dynamics

The existence of the super-rotation of Venus' atmosphere has been known from cloud top observations since the early 20th Century. Venus lacks a significant contribution from latent heating resulting from cloud formation, and Coriolis forces exhibit less of a restriction on equator to pole energy transport. Despite this apparent simplicity compared to Earth, a full understanding of its structure in the Venus atmosphere and mechanisms for its maintenance remains unresolved. Furthermore, 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 surface topography (i.e. the crests of continent-sized land masses), and recur regularly at similar times-of-day. Similar waves may have been seen by the VeGa balloons near the dawn terminator while flying over Aphrodite Terra. 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. Finally, models of exoplanetary atmospheres appear to predict even more exotic atmospheric dynamics regimes than is seen at Venus. Solving the problem of Venus' super-rotation (origin and maintenance) will be an important advance in atmospheric sciences in general, and lend credence to the modelling of exoplanetary atmospheres.

This investigation is focused on characterizing the current state of the deep atmosphere of Venus, semi-arbitrarily defined here as that portion of the atmosphere lying beneath the cloud tops around about 75 km. The reason for this is both theoretical and practical. At this altitude, the zonal wind speed reaches a maximum, before beginning to transition to the Subsolar-Antisolar flow. This altitude also exhibits a minimum in the vertical temperature profile. Each of these observations suggests a significant transition occurring at or near these altitudes. In a practical sense, 75 km represents an altitude above which it is difficult to obtain long-term and repeated measurement of atmospheric properties from an in situ platform. Above this altitude, the primary means of data acquisition must likely come from an orbital platform; while below this altitude, capability of measurement is expected to be possible from both in situ and remote means.

Investigation II.A.2. Upper Dynamics

While the RZS flow is prevalent in the low mesosphere, it begins to lose strength in the upper mesosphere with SSAS flow dominating near 100 km. However, as one moves into the thermosphere, RZS flow becomes prevalent once more. The reason for its reappearance is currently unknown, however recent studies suggest that the solar wind may be responsible.

Flow dynamics in the thermosphere are possible through observations of nightglow and auroral emission. Nightglow is atmospheric emission from photodissociated/ionized dayside atoms and molecules that are transported to the nightside and recombine to neutrals. As Venus has no intrinsic magnetic field, aurora refers to atmospheric emission due to particle precipitation from the solar wind. Additionally, auroral emission is present across the nightside of the planet.

One of the brightest Venusian nightglow features is the 1.27 µm O_2 ($^1\Delta_g$) emission which emits around 99 km near the antisolar point. VEX observations show that while this nightglow feature traces the SSAS flow, simultaneous observations of the NO UV bands (~115 km) is shifted three hours away from local midnight, towards the dawn sector, indicating the recurrence of the RZS flow. Additionally, Pioneer Venus Orbiter observations of auroral OI 130.4nm emission also exhibit an offset towards the dawn sector. Connected with the OI UV emission is the OI 557.7nm auroral emission which is present during solar storms and while it is anticipated to be offset as well, no spatial mapping has been conducted.

The recurrence of RZS flow in the thermosphere/ionosphere is an intriguing phenomena. Recent studies suggest that the ionosphere and neutral atmosphere are more intimately connected than previously believed. The orbital speed of Venus combined with the angle of the incoming solar wind and the strong connected of the ionosphere with the neutral atmosphere may be the important driver for thermosphere RZS flow.

Measurements are needed of auroral and other excited gas emissions driven by solar processes as well as the solar wind in order to understand the connections between the solar wind and the Venusian atmosphere. These observations could be accomplished through remote observations such as through an orbiter. Instruments needed to study the Venusian atmosphere and the solar wind include, but are not limited to, electron spectrometers, ion mass spectrometers, neutral particle detectors, UV and visible spectrographs and imagers, Solar Energetic Particle detectors, Langmuir probes, and magnetometers.

Investigation II.A.2. Mesoscale Processes

While the previous two investigations segregated global scale processes and observations according to vertical spatial domain (above and below an approximate altitude of 70 km, and the dominant processes in each), this investigation focuses on the smaller spatial scale processes and observations that can, taken as a whole, drive planetary atmosphere dynamics on either local or global scales. In a modelling sense, these processes would often be termed "sub-grid-scale" processes. In order to adequately model a planetary atmosphere, these processes must be sufficiently understood so as to be reliably parameterized in a general circulation model.

These processes include the behavior and evolution of convective cells, horizontal and vertical wave propagation, and other mesoscale structures. They can be of small enough spatial and/or temporal scales to be impractical targets for investigations focused on characterizing global scale processes. Nevertheless, such features and processes can be observed from orbit, as demonstrated by the discovery of numerous mesoscale features in both Venus Express and Akatsuki data. Direct *in situ* measurement of the local dynamics of isolated convective structures and/or wave propagation would also contribute to this investigation, but without global or regional contextual information, spatio-temporal degeneracies will remain, as they have for the interpretation of the VeGa balloon meteorological data.

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.

A proxy for the atmospheric dynamics is the rate and global distribution of lightning. Lightning has been mapped on the night side at middle and low latitudes by Pioneer Venus and at polar latitudes by Venus Express. More recent ongoing observations by the Lightning and Airglow Camera on Akatsuki promise to provide statistical assessments of the presence of lightning in the Venus atmosphere. NO_2 abundance in the Venus atmosphere suggests that lightning occurrence could be greater on Venus than on Earth [II.B: Atmospheric Chemistry].

The surface of Venus is an inhospitable 735K, with a mean surface pressure of about 92 bars. Despite the global cloud cover reflecting away ~75% of the incident solar flux, atmospheric CO_2 and H_2O drives a greenhouse effect that causes significant warming. However, despite such hostile surface conditions, Venus's clouds may also hosts one of the more favorable abodes for life in the solar system in its clouds where temperatures and pressures are considerably more Earth-like [II.B: Radiative Balance, Atmospheric Chemistry].

Of the 25% of incident solar flux that is not reflected away by the clouds, approximately half is absorbed in the cloud layers, making Venus unique among the terrestrial planets in that the atmosphere is heated primarily from above, rather than from below. Most of this radiation is absorbed by SO_2 and an unknown species whose existence has been known for decades, but whose identity remains a mystery [II.B: Unknown Absorber, Aerosols]. SO_2 has been shown to exhibit variability on timescales ranging from days to decades, with modelling suggesting variability on geological timescales as well [II.B: Aerosols, Volcanic Outgassing]. Other trace gasses have been shown to exhibit spatial and temporal variability (e.g., CO, OCS), which is likely linked to complex dynamical and chemical cycling [II.B: Atmospheric Chemistry].

<u>Investigation II.B.1. Radiative Balance</u>

The gradients of the upwelling and downwelling radiative fluxes, in both incident solar and emitted planetary infrared, determine the heating/cooling rates that can drive local and global atmospheric dynamics. These gradients are determined by absorbers and scatterers of both shortwave and longwave radiation distributed throughout the atmosphere, and which are involved in a variety of physical and chemical interactions. Although the radiative balance of Venus has been measured many times to reasonable precision, by the Pioneer Venus, Venera, and VeGa missions, there remains a mismatch between the measured radiative and dynamical parameters of the Venus atmosphere and those produced by models. 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 night side and day side can support the resolution of this Investigation. Such measurements can be made from probes, landers, or mobile aerial platforms. However, the utility of these measurements increases substantially with number of platforms, and with remote global context. High spectral resolution, full spectrum measurements of emitted and reflected radiation can make a significant contribution to this Investigation, but orbital assessments of radiative balance are only as good as the models of atmospheric constituents on which they are based built.

Investigation II.B.1. Atmospheric Chemistry

The constituents of the atmosphere of Venus are involved in a highly coupled system involving sulfur chemistry, organic chemistry, aerosol microphysics, and possibly even biological activity. Finding agreement between the chemical models of the Venus atmosphere and the 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 magnitude of the significance of the role of water in that process. The photochemistry and thermochemistry in the Venus atmosphere proceed in environments significantly dissimilar to Earth, and which have not yet been fully explored in the lab; improved observations of key constituents can constrain these models. Finally, the chemistry of super-critical carbon dioxide in the deep atmosphere remains unconstrained and under-studied, though recent research suggests that it could explain a long-standing puzzle regarding near-surface temperature profiles measured by descent probes.

An orbiter capable of high spectral resolution measurements across a broad region of the spectrum capable of retrieving high precision vertical profiles of chemically relevant species could make substantial progress toward this Investigation, especially when coupled with improved models of atmospheric chemistry in the Venus environment. In situ aerial platforms can make substantial progress on understanding the aqueous chemistry; much has been done for Earth. Finally, landers and descent probes capable of simultaneously measuring meteorological parameters and the mixing ratio of carbon dioxide (and other species) in the lowest 10 km can address the supercritical carbon dioxide question.

Investigation II.B.2. Aerosols

The Venusian aerosols have a major impact on the Venus greenhouse effect as well as the determination of its remotely observable properties. Furthermore, they are an integral part of the atmospheric chemistry system both as an active constituent—for example, in the distribution and formation of sulfuric acid from sulfur-bearing compounds and water vapor—and as a passive constituent—for example, in the facilitation of heterogeneous chemistry on the surfaces and interiors of cloud droplets. While the primary constituent of the upper clouds has long been known to be spherical particles of highly concentrated sulfuric acid with typical radii of one micron, the exact nature of the Venusian aerosols is incompletely known. A submicron mode of particles is known to exist in both the upper clouds, as well as in and below the middle and lower clouds. However, the size distribution of this smallest mode of particles at all altitudes remains somewhat underconstrained by the available data. Furthermore, in the upper clouds, the composition has been assumed to be sulfuric acid, but this has never been definitively shown. In and below the lower and middle clouds, the composition of this submicron aerosol mode remains similarly unknown. Finally, the largest mode of particles, the Mode 3 particles reported by the LCPS probes and VeGa landers in the middle and lower clouds, remains a controversial topic. The night side near infrared inhomogeneities are attributed largely to variations in the Mode 3 population, yet their existence remains unconfirmed and their composition unknown. It has been suggested that Mode 3 particles may have a crystalline component, or that they represent the tail end the distribution of large Mode 2 particles.

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

Investigation II.B.2. Unknown Absorber

Short-wavelength visible and near-ultraviolet light is unaccountably absorbed in Venus' upper atmosphere. The effects of this unknown absorber are strongest in the near-ultraviolet, but are apparent well into the wavelengths of visible light, and may have contributions elsewhere in the spectrum. The unknown absorber varies in strength over space and over a wide range of timescales. Its importance, besides that of an enduring curiosity, is that is responsible for at least half of the deposition of solar insolation into the atmosphere, and thus the thermal structure of the atmosphere. Numerous candidates have been proposed for its identification, including sulfur allotropes (S_x), iron chlorides ($FeCl_3$), and OSSO and its isomers. For example, OSSO provides a good spectral match to the UV absorption, and the high concentration of SO in the atmosphere implies that OSSO dimers should be present. But the unknown absorber might not be a single species: OSSO does not produce sufficient absorption near 400nm to match observations, and other likely candidates such as S_4 might be expected to provide the necessary opacity in this spectral region. Most recently, it has been suggested on the basis of comparison to the spectral properties of terrestrial acidophilic organisms that the unknown absorber could even be biological in origin.

Mass spectrometry is the measurement most likely to cleanly address this investigation. The Venus atmosphere would be ingested into the instrument while it moved through the region of the short-wave absorber, and the absorber's identity would be inferred directly or indirectly by the mass spectrum. The platform most appropriate to carry this mass spectrometer is likely a descent probe, or high-altitude airplane or balloon. In addition, high resolution spectroscopy from orbit or from an aerial platform can contribute to the investigation. However, the former is constrained by the complexity of the Venusian transmission spectrum, and the latter is constrained by its ability to determine global context. This Investigation would greatly benefit from multiplatform synergistic measurements.

Investigation II.B.3. Outgassing

Categorizing the amount and type of volcanism through planetary atmosphere measurements can provide a wealth of knowledge about the interiors of terrestrial planets (and exoplanets), including into the type(s) and composition of crust on a planet's surface (available for weathering and buffering the planet's atmosphere composition), the abundance of volatiles found in the planetary interior, the dynamics of the planetary interior, and potentially even the first order structure of the planet. Volcanism extreme enough to produce flood-like lavas on terrestrial planets in our Solar System requires either a very young planetary body or one with sustained vigorous convection, resulting in structures similar to mantle plume heads on Earth. Thus, the changing character of volcanism on planet through time will also provide a means of categorizing a planet's relative age and/or convective vigor and interior structure.

It is unknown whether Venus is currently volcanically active; although indirect evidence is building that volcanism is ongoing. For one, the massive H_2SO_4/H_2O clouds are most likely the products of volcanic outgassing of SO_2 in the past 10-50 My. This timescale is short compared to that of mantle convection, suggesting that volcanism continues to the present. Large differences in surface composition were identified in and around several massive shield volcanoes that were previously considered to be the youngest volcanic edifices on Venus. These compositional variations were inferred from near-IR surface emissivity, as measured by VIRTIS on Venus Express. Chemical interactions between emplaced lava and atmospheric gases are responsible for creating secondary minerals with different emissivity properties from basalts on timescales of 10^3 to 10^5 years. The short timescales required to modify the near-IR signature of basalts on Venus suggest that the emissivity anomalies associated with several large shield volcanoes are due to active volcanism.

On Venus, transient and high concentrations of SO_2 in the atmosphere and thermal anomalies on the surface have pointed to currently active volcanism, supported by a host of volcanic surface features and a young cratering-based surface age of 500–800 Ma. Venusian magmatism has resulted in rapid resurfacing in the past, which requires vigorous mantle convection and a high rate of mantle melting, and provides insight into Venus's mantle composition. The lack of plate tectonics on Venus suggests a conducting lithosphere on top of a convective mantle, where mantle plumes bring heat flow to the base of the lithosphere, from which it is conducted to the surface. This inefficient mode of heat transport may ultimately result in periodic complete overturn of the lithosphere and global resurfacing.

Direct imaging of hot spot volcanism and volcanic lakes at near-IR wavelengths from orbit has been suggested as a means to characterize the ongoing rate of volcanism on Venus. Although the observation statistics are poor, 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. Ultimately, in situ chemical measurements, including light isotope abundances, will be necessary to distinguish recent outgassing from the background atmosphere.

2.3. 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 the NASA Magellan mission provided the first global maps of Venus, many first-order issues regarding their interpretation and implications await resolution, which motivates collecting higher-resolution imagery, topography, and many other datasets that are available for other terrestrial planets.

Objective III.A. | What geologic processes have shaped the surface of Venus?

Many basic questions remain about the present-day surface, including its stratigraphic history [III.A.1. Geologic History, III.A.2. Crust, III.A.4. Absolute Ages], composition [III.A.1. Geochemistry], and potential for ongoing geologic activity [III.A.2. Geologic Activity].

<u>Investigation III.A.1. Geologic History</u>

Developing a stratigraphic history for the sequence of geological events is crucial for Venus or any planet, as it provides a framework for understanding the processes that shaped the coupled evolution of the surface, interior, and atmosphere. Volcanism and tectonism are ultimately driven by processes in the interior of Venus. The history of volcanic activity is a key constraint on the thermal evolution of Venus, and volcanism also contributes to development of the atmosphere. Similarly, the history of tectonic activity constrains the style and temporal evolution of convective circulation in the mantle. In addition, developing a stratigraphic history for Venus facilitates comparison with geologic processes on other terrestrial planets. This investigation is therefore considered Essential.

The 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 10-30 km/pixel. Ideally, a follow-up mission will provide order-of-magnitude improvement in resolution in these data sets, to 10-30 m/pixel for radar images and 0.5-1 km/pixel for altimetry. Global imaging coverage is preferred, but at a minimum all of the highland regions with obvious tectonic or volcanic features (~15% of the surface) plus a representative fraction of the regional plains should be mapped at high resolution. Radar imaging should be at least dual polarization, either circular or linear. 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 from a variable altitude aerial platform, deployed below the cloud deck, would be complementary to the greater spatial coverage possible from an orbiter.

<u>Investigation III.A.1. Geochemistry</u>

One of the biggest unknowns for Venus is its surface chemistry and mineralogy. Chemical analyses provided by the VENERA and VEGA missions, although engineering and scientific triumphs, do not permit detailed confident interpretation, such as are routine for terrestrial analyses and MER APXS rover analyses from Mars. In particular, their 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. Their analyses 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—they did not target sites in any of the highland areas: shield volcanos, tesserae, nor the unique plateau construct of Ishtar Terra. Given all these ambiguous results, rock types that may indicate igneous provenance cannot be identified. Similarly, no information is currently available to identify Venus mineralogy.

<u>Investigation III.A.2. Geologic Activity</u>

Interpretations of the geologic evolution of Venus have been contentious since the completion of the Magellan mission. Some investigators favor a model in which Venus experienced a catastrophic spasm of volcanism and tectonism 500-750 million years ago, with very little internally driven activity since that time. Other investigators favor a more gradual evolutionary history, with volcanism and tectonism continuing to the present day, although at a lower rate than on Earth. Direct detection of current volcanic or tectonic activity on Venus would provide important new evidence in this debate.

The key data sets for this investigation are radar imaging and topography as well as seismic measurements. Ideally both approaches will be used. 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. For this purpose, the new radar images would need to be similar in wavelength, incidence angle, and viewing direction to those obtained by Magellan. Differential InSAR altimetry from a future orbiter could detect small topographic changes (~10 cm vertically) due to active tectonism or volcanism, but would be limited to detecting changes that occur over the timescale of a future mission. Seismic measurements via a long-lived lander of seismicity induced by active tectonism or volcanism is the second key measurement type for this study. 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 the seismic measurements.

Several types of supporting measurements also are possible. The coupling of surface motion into the thick Venus atmosphere can produce propagating waves in the upper atmosphere that are detectable in high temporal resolution infrared images from orbit or by infrasound measurements on an aerial platform. This is considered a supporting measurement because such measurements do not contain as much detail as the original seismic waveform. Volcanic flows temporarily raise the surface temperature, which could be measured by infrared or microwave radiometry. Both techniques are limited to spatial resolutions of ~30-50 km/pixel, so measuring active lava flows in either case requires a very large flow. Finally, outgassing associated with large explosive volcanic eruptions may temporarily create a disequilibrium in the atmospheric composition which could be measured by entry probes, sondes, or aerial platforms, although an element of luck related to being in the right place at the right time is required.

Investigation III.A.2. Crust

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 tell us how much magmatism took place over that time period, and variations related to location of more ancient materials like tessera or more recent units like rift zones can provide the means to quantify activity outside of the resurfacing event. Information about the structure of the crust, including the thickness of plain 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. The timing and volume of volcanic flows would constrain whether volatiles were released gradually or catastrophically from the interior.

High precision and resolution gravity and altimetry data provided, for instance, by a GRAIL-like gravimeter system and a global stereo topography, would be essential to determine the structure of the crust, including this thickness, changes of density with depth, and the thickness and density of surface units such as regional plain units 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. This can only be achieved by a radar operating in SAR mode from an orbital or aerial platform. Transmitting and receiving circular polarizations, as done by Arecibo and other planetary radars, would also be important. 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.

Investigation III.A.4. Absolute Ages

In the absolute sense, nothing is known about the surface age of rocks on Venus' surface. Although impact ages suggest it may be quite young, the possibility remains that some units might date from a time when Venus was habitable. 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. So 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 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.

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.

Investigation III.B.1. Local Weathering

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 oxide phases such as magnetite and hematite. This investigation would search for the presence of dehydrated minerals such as anhydrite and well as the possible presence of alteration phases from basaltic minerals. Such investigations could involve in situ instruments for mineralogy, including visible-mid-IR and Raman spectroscopies. Drilling to probe beneath surface alteration could provide valuable information on the depth of alteration as well as the underling mineralogy.

Investigation III.B.2. Global Weathering

Among the most striking findings of the Magellan mission was the discovery of great differences in radar backscatter brightness with elevation: the highlands are significantly brighter than the lowlands. After considerable debate within the community and both thermodynamic and experimental studies, it can be concluded that only HgTe (the mineral coloradoite) and pyrite

(FeS_2) remain as possible candidate substances that might explain the elevation change. However, such approaches depend on assumed surface geochemistry and oxidation state, both of which are poorly known. Possible investigations to resolve these questions are two-fold. Orbital spectroscopy utilizing the windows in the ~1-micron region make it possible to distinguish key rock types (e.g., basalt vs. granite) and can differentiate among phase changes with elevation, such as magnetite hematite, and pyrite. Surface mineralogy could also be measured using in situ visible-mid-IR spectroscopy, while Mossbauer spectroscopy could measure oxidation state.

Investigation III.B.3. Chemical Interactions

Concentrations of trace gases in the deep atmosphere have been estimated through remote sensing observations in the Venus near-infrared nightside spectral windows, but many crucial species (e.g. CO, OCS, SO_2) can only be measured at elevated altitudes near the base of the cloud deck through this method and not in the lowest atmospheric scale height where surface-atmosphere interactions will occur. Therefore, inferences about their near-surface concentration must be made through extrapolation of their observed higher elevation concentrations, and through model predictions. For instance, Venus Express and ground-based observations suggest OCS-CO anticorrelation at 30-45 km that may be related to chemical conversation between these species at the atmosphere-surface interface: e.g., CO may react with pyrite on the surface to form OCS. Other surface-atmosphere reactions may occur: 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. Venera landing sites indicate some rocks at the Venusian surface may be enriched in S relative to Earth basalts, suggesting processes of basaltic weathering. Secondly, SO_3 in the atmosphere is predicted to react with Ca-bearing silicates to form $CaSO_4$, anhydrite, thus reducing the proportion of atmospheric sulfate. There are suggestions that atmospheric halogens could exchange with the surface, perhaps reducing the Cl/F ratio by formation of Cl-bearing phosphate phases. Third, there is strong evidence in equatorial and northern highlands that atmosphere-surface chemistry varies with elevation. And, if Venus' volcanic rocks include hydroxy-bearing igneous minerals (like amphibole or biotite), their decomposition should release hydrogen (with D/H values of the interior) to the atmosphere.

In-situ direct measurements of 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 could be accomplished via descent probes with mass spectrometers designed to sample Venus' lower atmosphere as the probe descended, and then for as long as they survive on the surface. Determining gradients on a regional scale would be enabled by orbital or balloon 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. Additionally, experiments at the relevant temperature and pressure of the Venus surface environment could answer questions of which surface-atmosphere chemical reactions are plausible to explain observed gas concentrations.

3. Linking the 2019 GOI to Previous Versions and Other VEXAG Documents

Investigations from the 2016 GOI are included in the current version. However, the 2016 Goals focused separately on 1) the atmosphere, 2) surface and interior processes, and 3) the atmosphere-surface interface. The 2019 GOI blends Investigations to achieve big-picture goals, and has been iterate to serve as the foundation for the VEXAG Roadmap and Technology plans.

Appendix 1: 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, I.A.1. was higher priority than both I.B.1. and I.A.2. in the 2016 GOI. In contrast, Investigations I.A.1. Hydrous Origins and I.B.1. Isotopes have equal (highest) priority according to this 2019 GOI.

Investigation in 2019 GOI	Related Investigation in 2016 GOI
I.A.1. Hydrous Origins	III.A.2. III.A.3.
I.A.1. Crustal Recycling	II.A.3.
I.A.2. Atmospheric Losses	I.A.2.
I.A.3. Magnetism	II.A.3.
I.B.1. Isotopes	I.A.1. I.A.2. II.A.2. III.A.1. III.B.1. III.B.4.
I.B.1. Lithosphere	II.A.3.
I.B.2. Heat Flow	
I.B.2. Core	II.B.4.
I.B.4. Deep Structure	III.A.3. II.B.4.
II.A.1. Deep Dynamics	I.B.1. I.B.3. I.C.1.
II.A.1. Upper Dynamics	I.B.1. I.B.3.
II.A.2. Mesoscale Processes	I.B.1. I.B.3. I.C.1.
II.B.1. Radiative Balance	I.B.2.
II.B.1. Interactions	I.C.1.
II.B.2. Aerosols	I.C.1.

	I.C.2. I.C.3.
II.B.2. Unknown Absorber	I.C.2. I.C.4.
II.B.3. Outgassing	III.B.4.
III.A.1. Geologic History	II.A.1. II.B.6.
III.A.1. Geochemistry	II.B.1. II.B.2. II.B.5.
III.A.2. Geologic Activity	II.A.4.
III.A.2. Crust	II.B.3. II.B.6.
III.A.4. Absolute Ages	II.A.5.
III.B.1. Local Weathering	III.B.2.
III.B.2. Global Weathering	III.B.2.
III.B.3. Chemical Interactions	III.B.3.

Appendix 2: Linking the 2019 VEXAG GOI and Roadmap

VEXAG GOI			Roadmap Mission Modalities													
			Class	Orbiter	Orbiter	Orbiter	Atmospheric Probes			Surface Platform (lifetime)			Aerial Platform (altitude)			Overall
Goal	Objective	Investigation	Platform	Surface/Interior	Atmosphere	SmallSat	Skimmer	Probe	Sonde	Short	Long	Advanced	Fixed	Variable	Variable+	
			Timing	Near	Near	Near	Near	Near	Mid	Near	Mid	Far	Near	Mid	Far	
I. Early evolution and potential habitability	Did Venus have liquid water?	I.A.1.Hydrous Origins		CA (yellow)	CA (yellow)	CA (yellow)				C (green)	C (green)	C (green)			C (green)	(blue)
		I.A.1.Crustal recycling		C (green)						C (green)	C (green)	C (green)	CA (yellow)	CA (yellow)	CA (yellow)	(blue)
		I.A.2.Atmospheric losses			A (blue)	AN (blue)										(blue)
		I.A.3.Magnetism			A1 (yellow)	A1 (yellow)				C (yellow)	C (yellow)	C (yellow)	A2 (blue)	A2 (blue)	A2 (blue)	(blue)
	How does Venus inform possible pathways for planets?	I.B.1.Isotopes					C (green)	A (blue)	A (blue)	A (blue)	A (blue)	A (blue)	A (blue)	A (blue)	A (blue)	(blue)
		I.B.1.Lithosphere		(blue)	A1 (yellow)	A1 (yellow)					CN (yellow)	CN (green)	A2 (blue)	A2 (blue)	A2 (blue)	(blue)
		I.B.2.Heat flow		(green)								(green)				(blue)
		I.B.2.Core		(green)							N (blue)	N (blue)				(blue)
		I.B.4.Deep structure		(yellow)							N (green)	N (green)				(green)
II. Atmospheric dynamics and composition	What drives global dynamics?	II.A.1.Deep dynamics			CA1 (blue)	CA1 (green)		C (yellow)	C (yellow)		(yellow)	(yellow)	CA2 (yellow)	CA2 (yellow)	CA2 (yellow)	(blue)
		II.A.1.Upper dynamics			A (blue)	A (blue)	C (yellow)									(blue)
		II.A.2.Mesoscale processes			CA1 (green)	CA1 (yellow)		C (yellow)	C (yellow)				CA2 (yellow)	CA2 (green)	CA2 (green)	(green)
	What governs composition and radiative balance?	II.B.1.Radiative balance			CA1 (green)	CA1 (green)		CA4 (yellow)	CA4 (yellow)	CA4 (yellow)	CA3 (yellow)	CA3 (yellow)	CA2 (green)	CA2 (green)	CA2 (green)	(green)
		II.B.1.Interactions			(green)	N (yellow)		C (green)	C (green)				A (blue)	A (blue)	A (blue)	(blue)
		II.B.2.Aerosols			A3 (yellow)	A3 (yellow)		A2 (green)	A2 (green)	A2 (yellow)	A2 (yellow)	A2 (yellow)	C (green)	A1 (blue)	A1 (blue)	(blue)
		II.B.2.Unknown absorber			CA1 (green)	CA1 (green)		(yellow)	(yellow)				CA2 (yellow)	CA2 (green)	CA2 (green)	(green)
		II.B.3.Outgassing		C (green)	CA1 (green)	CA1 (green)		C (yellow)	C (yellow)	C (yellow)	C (green)	C (green)	(yellow)	(green)	C (green)	(green)
III. Geologic history and processes	What geologic processes shape the surface?	III.A.1.Geologic history		(blue)											C (yellow)	(blue)
		III.A.1.Geochemistry		C (yellow)	C (yellow)	C (yellow)		(yellow)	(yellow)	C (green)	C (green)	C (green)			C (green)	(blue)
		III.A.2.Geologic activity		C (green)	A1 (yellow)	A1 (yellow)		A2 (yellow)	A2 (yellow)		CN (green)	CN (green)	A3 (yellow)	A3 (yellow)	A3 (yellow)	(blue)
		III.A.2.Crust		(blue)	CA1 (yellow)	CA1 (yellow)					CN (green)	CN (green)	CA2 (blue)	CA2 (blue)	CA2 (blue)	(blue)
		III.A.4.Absolute ages										(green)				(green)
	How do the atmosphere and surface interact?	III.B.1.Local weathering		C (yellow)	C (yellow)	C (yellow)		C (green)	C (green)	A (blue)	A (blue)	A (blue)	C (yellow)	C (yellow)	C (yellow)	(blue)
		III.B.2.Global weathering		(green)	(green)	(green)				A (green)	A (green)	A (green)	C (yellow)	C (yellow)	C (yellow)	(blue)
		III.B.3.Chemical interactions		C (yellow)	C (yellow)	C (yellow)		A (blue)	A (blue)	A (blue)	A (blue)	A (blue)	C (yellow)	C (yellow)	C (green)	(blue)

Color Code	Meaning
(blue)	Comprehensive: Platform enables completing all of the investigation
(green)	Substantial: Platform enables completing most of the investigation
(yellow)	Supporting: Platform enables completing some of the investigation

Symbol	Meaning
A	Alternate: Only one of the marked platforms is required to complete the investigation.
1 or 2	Alternate categories: One of the alternate platforms from each category is required for the investigation.
C	Complementary: Instrumentation on multiple platforms benefits the investigation and is not redundant.
N	Network: Simultaneous observations from multiple platforms at different locations would benefit the investigation.

Appendix 3: List of Acronyms

Under construction.