Venus White Paper for Planetary Sciences Decadal Survey Inner-Planets Panel

Venus Exploration Goals, Objectives, Investigations, and Priorities

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ENDORSEMENTS: See appendix

VEXAG Goals, Objectives, and Investigations

Why Venus now?

Venus proximity to Earth and its similarity in size and bulk density to Earth's have earned it the title of "Earth's twin". As well, the lack of seasons and overall regular nature of the surface—with no land/water contrasts to help generate weather nor large oceans to help transport heat and momentum—seemingly renders Venus a relatively simple planet to understand. Yet we understand very little about this very alien world next door. Indeed, the contrast between Venus' hellish 450°C surface temperature, sulfuric acid clouds, and its divergent geologic evolution has challenged our fundamental understanding of how terrestrial planets, including Earth, work. The absence of plate tectonics on Venus helped move models away from an emphasis on buoyancy to an understanding of the function of lithospheric strength, convective vigor, and the role of volatile history in controlling these processes. Venus is the planet where the importance of the greenhouse effect was first realized, and where winds blow with hurricane force nearly everywhere across the planet, from the first km above the ground to above 100 km altitude and from the equator to the high polar region. What powers such global gales when the planet itself rotates at a speed slower than the average person can walk on Earth is unknown?

The study of the links between surface, interior, and climatic processes on Venus has reinforced the idea that Venus could represent the fate of the Earth. The realization that two such similar planets could produce this extreme range of processes and conditions makes Venus an essential target for further exploration as we move out in the universe and discover Earth-like planets beyond our solar system.

Recent results from Mars show that liquid ground water was limited to the first billion years of its evolution, during its geologically active period. Venus Express has provided new reasons to explore Venus now. Surface thermal emissivity observations suggest tantalizing evidence of more evolved crustal plateaus, suggesting past oceans. Observations of atmospheric cyclones show structure nearly identical to those on Earth. As climate evolution comes into sharp focus on Earth, we must resume exploration of the planet that serves as an extreme end member.

Overarching Theme for Venus Exploration

With the context provided by the 2003 NRC Decadal Survey [1, 2], the 2006 Solar System Roadmap [3], and the 2007 NASA Science Plan [4], VEXAG has adopted an overarching theme for Venus exploration: **Venus and Implications for the Formation of Habitable Worlds**. This theme is supported by three goals and prioritized objectives and investigations (Table 1-1).

1. **Origin and Evolution**: How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and conditions of habitable environments on Venus and similar extrasolar systems?
2. **Venus as a Terrestrial Planet**: What are the processes that have shaped and still shape the planet?
3. **Climate Change and the Future of Earth**: What does Venus tell us about the fate of Earth's environment?

Table 1-1. Venus and Implications for the Formation of Habitable Worlds

Goal	Objective	Investigation
Origin and Evolution	Understand atmospheric evolution	Characterize elemental composition and isotopic ratios of noble gases in the Venus atmosphere, especially Xe, Kr, ^{40}Ar, ^{36}Ar, Ne, ^{4}He, ^{3}He, to constrain origin and sources and sinks driving evolution of the atmosphere.
		Determine isotopic ratios of H/D, $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{34}S/^{32}S$ and $^{13}C/^{12}C$ in the atmosphere to constrain paleochemical disequilibria, atmospheric loss rates, the history of water, and paleobiosignatures.
	Seek evidence for past changes in interior dynamics	Characterize the structure, dynamics, and history of the interior of Venus, including possible evolution from plate tectonics to stagnant-lid tectonics.
		Characterize the nature of surface deformation over the planet's history, particularly evidence for significant horizontal surface movement.
		Characterize radiogenic ^{4}He, ^{40}Ar and Xe isotopic mixing ratios generated through radioactive decay to determine the mean rate of interior outgassing over Venus' history.
	Determine if Venus was ever habitable	At the surface, identify major and minor elemental compositions (including H), petrology, and minerals in which those elements are sited (for example, hydrous minerals to place constraints on past habitable environments).
		Characterize gases trapped in rocks for evidence of past atmospheric conditions.
Venus as a Terrestrial Planet	Understand what the chemistry and mineralogy of the crust tell us about processes that shaped the surface of Venus over time	Characterize geologic units in terms of major, minor, and selected trace elements (including those that are important for understanding bulk volatile composition, conditions of core formation, heat production, and surface emissivity variations), minerals in which those elements are sited, & isotopes.
		Characterize the chemical compositions of materials near Venus' surface as a function of depth (beyond weathering rind) to search for evidence of paleochemical disequilibria and characterize features of surface rocks that may indicate past climate or biogenic processes.
		Assess the petrography (shapes, sizes, & mineral grain relationships) & petrology (formation characteristics) of surface rocks to aid in interpretation of chemical and mineralogical characterization.
		Determine the physical properties and mineralogy of rocks located in a variety of geologic settings, including meteoritic and crater ejecta, volcanic flows, aeolian deposits, and trace metals in the high radar reflectivity highlands.
		Characterize surface exposure ages through measurements of weathering rinds.
	Assess the current structure and dynamics of the interior	Characterize the current structure and evolutionary history of the core.
		Place constraints on the mechanisms and rates of recent resurfacing and volatile release from the interior.
		Determine the structure of the crust, as it varies both spatially and with depth, through measurements of topography and gravity to high resolution.
		Measure heat flow and surface temperature to constrain the thermal structure of the interior.
		Measure the magnetic field below the ionosphere and characterize magnetic signature of rocks in multiple locations.
		Characterize subsurface layering and geologic contacts to depths up to several km.
		Determine the moment of inertia and characterize spin-axis variations over time.

Table 1-1. Venus and Implications for the Formation of Habitable Worlds

Goal	Objective	Investigation
Venus as a Terrestrial Planet	Characterize the current rates and styles of volcanism and tectonism, and how have they varied over time	Characterize active-volcanic processes such as ground deformation, flow emplacement, or thermal signatures to constrain sources and sinks of gases affecting atmospheric evolution.
		Characterize active-tectonic processes through seismic, ground motion, or detailed image analysis.
		Characterize the materials emitted from volcanoes, including lava and gases, in terms of chemical compositions, chemical species, and mass flux over time.
		Characterize stratigraphy of surface units through detailed topography and images.
		Assess geomorphological, geochemical, and geophysical evidence of evolution in volcanic styles.
	Characterize current processes in the atmosphere	Characterize the sulfur cycle through measurements of abundances within the Venus clouds of relevant gaseous and liquid/solid aerosol components such as SO_2, H_2O, OCS, CO, and sulfuric acid aerosols (H_2SO_4).
		Determine the mechanisms behind atmospheric loss to space, the current rate, and its variability with solar activity.
		Characterize local vertical winds and turbulence associated with convection and cloud-formation processes in the middle cloud region, at multiple locations.
		Characterize superrotation through measurements of global-horizontal winds over several Venus days at multiple-vertical levels (day and night) from surface to thermosphere.
		Investigate the chemical mechanisms for stability of the atmosphere against photochemical destruction of CO_2.
		Characterize local and planetary-scale waves, especially gravity waves generated by underlying topography.
		Measure the frequencies and strengths of lightning and determine role of lightning in generating chemically-active species (e.g., NO_x).
		Search for and characterize biogenic elements, especially in the clouds.
Climate Change and the Future of Earth	Characterize the Venus Greenhouse	Determine radiative balance as a function of altitude, latitude, and longitude.
		Measure deposition of solar energy in the atmosphere globally.
		Determine the size, distribution, shapes, composition, and UV, visible, and IR spectra, of aerosols through vertical profiles at several locations.
		Determine vertical-atmospheric temperature profiles and characterize variability.
	Determine if there was ever liquid water on the surface of Venus	Determine isotopic ratios of H/D, $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{34}S/^{32}S$ $^{13}C/^{12}C$ in solid samples to place constraints on past habitable environments (including oceans).
		Identify and characterize any areas that reflect formation in a geological or climatological environment significantly different from present day.
	Characterize how the interior, surface, and atmosphere interact	Determine abundances and height profiles of reactive atmospheric species (OCS, H_2S, SO_2, SO_3, H_2SO_4, S_n, HCl, HF, SO_3, ClO_2 and Cl_2), greenhouse gases, H_2O, and other condensibles, in order to characterize sources of chemical disequilibrium in the atmosphere.
		Determine rates of gas exchange between the interior, surface and atmosphere.

Interacting with the Venus community during the first three VEXAG meetings, the VEXAG focus groups on the atmosphere, the solid planet, and technologies developed objectives and investigations needed for each of these three goals. Given their interdisciplinary nature, many investigations were assigned to several goals and objectives. In 2008 the Venus Science and Technology Definition Team (STDT) [5] streamlined these so that each investigation is listed only once. During the February 2009 VEXAG meeting, the Venus community reviewed a revised set of the goals, objectives, and investigations, taking into account the STDT recommendation as well as new developments in Venus science. An updated set of goals, and prioritized objectives, and investigations is presented here (Table 1-1), based on the February 2009 meeting recommendations as well as an April 2009 Web-based survey.

Within each of these Venus exploration goals, there is a series of objectives, with priority rankings based on scientific importance. Within each objective are investigations that are collectively needed to achieve that objective. These investigations are generally scientific, and may be addressed by single or multiple missions and/or instruments. Also, significant technology development may be required for the development of instruments capable of performing the Investigations. These investigations are listed in priority order within each objective.

Goal 1. Origin and Evolution: How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and conditions of habitable environments on Venus and similar extrasolar systems?

Goal 1 involves understanding the origin and evolution of Venus, from its formation to today. Like Earth and Mars, the atmosphere of Venus today seems to have substantially evolved from its original composition. Whether the major processes that shaped the atmospheres of Earth and Mars—such as impacts of large bolides and significant solar wind erosion—also occurred on Venus is largely unknown. Detailed-chemical measurements of the composition of the atmosphere (in particular, the noble gases and their isotopes) will provide fundamental insight into the origin and evolution of Venus.

The surface of Venus appears to have been shaped, for the most part, within the geologically recent past, likely within the past 500 million to one billion years. Venus' surface may contain evidence of the planet's earlier history and origin (which may be accessible through a more complete characterization of the surface than previously accomplished), as well as a deeper understanding of the nature and evolution of the interior dynamics. In addition, detailed-chemical measurements of the composition of the atmosphere (in particular, the noble gases and their isotopes) provide additional information about the origin and evolution of Venus. Of particular interest is the possibility that Venus, early in its history, had long-lived oceans and a climate amenable to the development and evolution of life—possibilities that are not excluded by current knowledge.

A prime objective of Goal 1 is to understand the sources of materials that formed Venus and their relationship to the materials that formed the other terrestrial planets. Of particular interest is whether or not Venus possesses a secondary atmosphere—like the atmospheres of Earth and Mars— and, if so, what processes eroded the original atmosphere (e.g., impact by large bolides, solar wind erosion), supplied additional gases (e.g., cometary impacts), and led several billion years ago to a secondary atmosphere.

The second objective of Goal 1is to understand the processes that subsequently modified the secondary (or original) atmosphere, leading to the current inventory of atmospheric gases, which is so unlike those present on Earth. Detailed-chemical measurements of the composition of the atmosphere provide such fundamental information. Also, it is important to seek evidence for the evolution of processes in the interior, such as the transition between plate tectonics to stagnant lid tectonics and the rate of interior outgassing.

The third objective of Goal 1 is to determine whether Venus was ever habitable. Of particular interest is the search for earlier wetter and cooler periods via chemical/elemental, petrological, and morphological evidence in the rock record, as well as via chemical tracers in the atmosphere that provide insights into degassing and the development of runaway greenhouse.

Goal 2. Venus as a Terrestrial Planet: What are the processes that have shaped and still shape the planet?

Although Earth and Venus are 'twin' planets in size and mass, Venus' surface at this time is clearly hostile to carbon-water-based organisms. Venus' atmosphere, which is far denser than Earth's, is composed mostly of carbon dioxide with abundant sulfur oxides and a significant deficit of hydrogen. Venus' atmosphere moves (everywhere except within a few hundred meters of the surface) with hurricane-force velocities reaching 60 times planetary rotation speed near the cloud tops. How a planet that revolves more slowly than a normal walking speed can generate such winds globally is an enigma. Venus' surface is composed mostly of Earth-like igneous rocks (basalt) at an average temperature of ~460 ºC, precluding the presence of liquid water. Venus' highlands are mantled by deposits of an electrically-conductive or semiconductive material.

Venus' geologic processes are also largely dissimilar from those on Earth, aside from volcanic eruptions. The surface of Venus appears to have been resurfaced within the past 500 million to one billion years, obscuring possible signatures of earlier geological episodes. The nature and duration of this resurfacing remain enigmatic. Subsequent to resurfacing, styles of tectonism and volcanism evolved as the planet cooled, such that the thermal/dynamic regime of the planet is now thought to be a convection under a stagnant or sluggish lid. There is no manifestation of the global-plate tectonic processes like those on Earth. Analyses of gravity and topography data suggest that Venus has a comparable number of active large mantle plumes as Earth, as well many hundreds of smaller scale plumes that may also be active. Although there is little information on current levels of volcanic or tectonic activity, some atmospheric data suggest that Venus is still volcanically active. Exploring and characterizing processes on and in Venus will help us understand dynamical, chemical, and geologic processes on other planets throughout our galaxy.

Within Goal 2, four science objectives are focused on improving our understanding of the surface and interior of Venus. The highest-priority objective of Goal 2 is to better understand what the chemistry and mineralogy of the crust tell us about processes that shaped the surface of Venus over time. Our limited knowledge of the crustal composition and properties of surface rocks is derived from a handful of in situ measurements made by the Soviet Venera and VEGA landers. New data on major and minor trace elements, as well as mineralogy of rocks in a variety of settings are required to place constraints on volcanic processes (basaltic vs silicic) as well as to place bounds on the role of water in Venus' past.

The second objective of Goal 2 is to assess the current structure and dynamics of the interior. How Venus transfers heat to the surface (through periodic catastrophic overturning events, or more gradually over time) is still a mystery. Scientific investigations within this objective are focused on placing constraints on the evolution of the core over time and quantifying the mechanisms and rates of volcanic resurfacing.

The third objective of Goal 2 is to characterize the current rates and styles of volcanism and tectonism, and how they have varied over time. As noted above, current evidence points to the possibility that Venus may still be volcanically and/or tectonically active. Resolution of this important question has significant implications for placing bounds on resurfacing rates and provides the motivation for deploying long-lived seismic stations.

The fourth and final objective of Goal 2 is to characterize current processes in the atmosphere. This objective is focused on continuing to improve our understanding of physical and chemical processes that influence today's atmosphere. The Venus Express mission has provided new insights into the dynamics of the south polar vortex, but major issues (e.g., super rotation) remain a mystery. Key investigations here include characterization of the sulfur cycle and development of a better understanding of dynamics and radiative balance.

Goal 3. Climate Change and the Future of Earth: What does Venus tell us about the fate of Earth's environment?

Although the terrestrial planets formed at about the same time within the inner solar system, from similar chemical and isotopic reservoirs, they have followed very different evolutionary paths. In particular, Venus and Earth, which formed at similar distances from the Sun with nearly identical masses and densities, currently have vastly different atmospheres, surface environments, and tectonic styles. It has been suggested that Venus may have been more Earth-like earlier in its history and then evolved to its current state, and that Earth may ultimately transform to a hot, dry, inhospitable planet like Venus. Thus, understanding the interior dynamics and atmospheric evolution of Venus provides insight into the ultimate fate of Earth.

The first objective of Goal 3 is to characterize the present-day greenhouse of Venus. Although significant progress has been made with past and current missions, there are still several important areas of uncertainty. Investigations are needed to understand the current climate balance, in a way that will facilitate improved predictions of Earth's future climate, focus on improved measurements of the spatial and temporal distributions of radiative balance, temperature structure, and cloud aerosol properties.

The second objective of Goal 3 is to determine if liquid water ever existed on the surface of Venus. It seems certain that Venus formed with much more water than observed in the present atmosphere. Energy balance considerations taking into account the faint young sun imply that Venus should have had liquid water early on in its history. Yet direct observational confirmation of this hypothesis is lacking. Thus, this confirmation would have important implications for understanding the evolution of terrestrial planet environments and habitability. It would also support the hypothesis that, as solar luminosity increases, Earth's future evolution will resemble the past evolution of Venus. Investigations for this objective include determining isotopic ratios in solid samples and characterizing the conditions of origin of surface rocks.

The third objective of Goal 3 is to characterize how the Venus interior, atmosphere, and surface are interacting. It has become clear that, as on Earth, the climate balance of Venus reflects a dynamic balance between geologic and atmospheric processes. A detailed understanding of these interactions requires investigations to determine the abundances and vertical profiles of several reactive species, greenhouse gases, and condensable species, as well as the rates of gas exchange between the surface, atmosphere, and interior.

Pathways to Realizing the Goals of Venus Exploration

The technological challenges facing a sustained investigation of the deep atmosphere, surface, and sub-surface of Venus are substantial. These challenges are addressed in a companion Venus white paper by Cutts, Balint, and others. New missions to explore Venus and its environment continue to be conceived and developed internationally. The European Space Agency's Venus Express mission, which continues to collect observations from its high-eccentricity polar orbit since its arrival at Venus in April 2006, is anticipated to operate through the end of 2013. Japan in May 2010 will launch the Venus Climate Orbiter, which will arrive at Venus in December 2010 and collect observations for two years from a near-equatorial, eccentric orbit. Concurrent observations of the Venus atmosphere from two different vantage points from these two missions will be used to understand the atmospheric processes, such as the evolution and maintenance of the hemispheric vortex.

Understanding the surface/interior of Venus and its atmosphere presents different technological and observational challenges. The extreme heat and high surface pressure—and their affects on the mobility, available power, as well as the long-term survival of instruments and communications capability—present formidable issues that require an investment in technology. Similarly, observing the deep atmosphere and its component processes globally over extended time (at least three solar days) requires a fleet of observing platforms (orbit and multiple atmospheric levels). The observing platforms will enable us to make key observations that will help us understand the Venus atmosphere. For example, the similarities between the circulation of terrestrial tropical cyclones to the northern and southern hemispheric vortices on Venus will enable us to infer the structure of the Venus circulation from its terrestrial analogue despite the differences in physical scale and sources of energy. These required key observations are described in a companion Venus white paper on Venus atmospheres by Limaye and others.

References

All of the Venus White Papers for the Planetary Sciences Decadal Survey are posted on the VEXAG web site <http://www.lpi.usra.edu/vexag/>.

[1] National Research Council New Frontiers in the Solar System: An Integrated Exploration Strategy (also known as the NRC Decadal Survey for Solar System Exploration) (2003): http://www.nap.edu/catalog.php?record_id=10432#toc

[2] Crisp, D., et al., "Divergent Evolution Among Earth-like Planets: The Case for Venus Exploration," The Future of Solar System Exploration, 2003–2013, Community Contributions to the National Research Council (NRC) Solar System Exploration Survey (Mark Sykes, Ed.), ASP Conference Series, vol. 272, pp. 5–34, 2002.

[3] NASA Solar System Exploration Roadmap (2006): http://solarsystem.nasa.gov/multimedia/downloads.cfm

[4] NASA Science Plan for NASA's Science Mission Directorate 2007–2016: http://science.hq.nasa.gov/strategy/Science_Plan_07.pdf

[5] NASA's Flagship Mission to Venus: Final Report of the Venus Science and Technology Definition Team, April 2009, http://vfm.jpl.nasa.gov

Appendix: Endorsements

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