

1. Venus Goals, Objectives, and Investigations

This section—excerpts from the Venus Goals, Objectives, and Investigations White Paper, submitted to the NRC Decadal Survey Inner Planets Subpanel—provides an overview of the Venus prioritized goals, objectives, and investigations, which were revised by the Venus Science and Technology Definition Team (STDT) during their development of the Venus Flagship mission concept in 2008–2009. The Goals, Objectives, and Investigations are a living document, and will be updated as needed by the Venus science community. For example, new discoveries, interpretations, technologies or missions might result in proposed changes to document.

1.1. *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". The lack of seasons and oceans to help transport heat and momentum suggest that the Venus atmosphere would be relatively simple. Yet we understand very little about this very alien world next door. Indeed, the contrast between the extreme 450°C Venus surface temperature, sulfuric acid clouds, and its divergent geologic evolution have 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 supports 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. Europe's Venus Express has provided new reasons to explore Venus now. Surface thermal emissivity observations suggest tantalizing evidence of more evolved crustal plateaus, suggesting possible past oceans. Observations of surface emissivity variations from Venus Express suggest the presence of geologically recent flows. This recent volcanism has important implications for both interior dynamics and present day climate. As climate evolution comes into sharp focus on Earth, we must resume exploration of the planet that serves as an extreme end member.

1.2. *Overarching Theme for Venus Exploration*

With the context provided by the Venus White Papers prepared for the Planetary Science Decadal Survey, VEXAG adopted an overarching theme for Venus exploration: **Venus and Implications for the Formation of Habitable Worlds**. This theme is supported by three equally important goals with their prioritized objectives and investigations (Table 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?
- **Venus as a Terrestrial Planet:** What are the processes that have shaped and still shape the planet?
- **Climate Change and the Future of Earth:** What does Venus tell us about the fate of Earth's environment?

1.3. Venus Exploration Goals

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 insights 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. The Venus surface, however, 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. In summary, the objectives of Goal 1 are to:

- (1) Understand the sources of materials that formed Venus and their relationship to the materials that formed the other terrestrial planets.
- (2) Understand the processes that subsequently modified the secondary (or original) atmosphere, leading to the current inventory of atmospheric gases (which are so unlike those present on Earth).
- (3) Determine whether Venus was ever habitable.

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, the Venus surface at this time is clearly hostile to carbon-water-based organisms. The 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. The 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. The Venus surface is composed mostly of Earth-like igneous rocks (basalt) at an average temperature of ~460 °C, precluding the presence of liquid water. The 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 are no manifestations 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 are needed to understand dynamical, chemical, and geologic processes on other planets throughout our galaxy. The objectives of Goal 2 are to:

- (1) Understand what the chemistry and mineralogy of the crust tell us about processes that shaped the surface of Venus over time,
- (2) Assess the current structure and dynamics of the interior, and
- (3) Characterize the current rates and styles of volcanism and tectonism, and how they have varied over time, and (4) characterize current processes in the atmosphere.

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, now 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. It has become clear that, as on Earth, the climate balance of Venus reflects a dynamic balance between geologic and atmospheric processes. Thus, understanding the interior dynamics and atmospheric evolution of Venus provides insight into the ultimate fate of Earth. The objectives of Goal 3 are to:

- (1) Characterize the present-day greenhouse of Venus,
- (2) Determine if liquid water ever existed on the surface of Venus, and
- (3) Characterize how the Venus interior, atmosphere, and surface are interacting.

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 the 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.

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 ₂ O, OCS, CO, and sulfuric acid aerosols (H ₂ SO 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
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, 15N/14N, 17O/16O, 18O/16O, 34S/32S 13C/12C 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 ₂ S, SO ₂ , SO ₃ , H ₂ SO ₄ , Sn, HCl, HF, SO ₃ , ClO ₂ and Cl ₂), greenhouse gases, H ₂ O, 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.