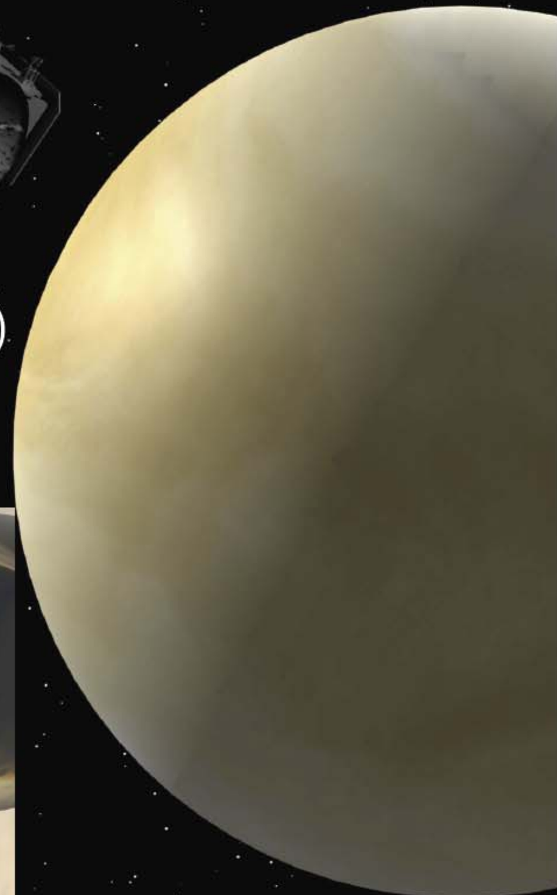
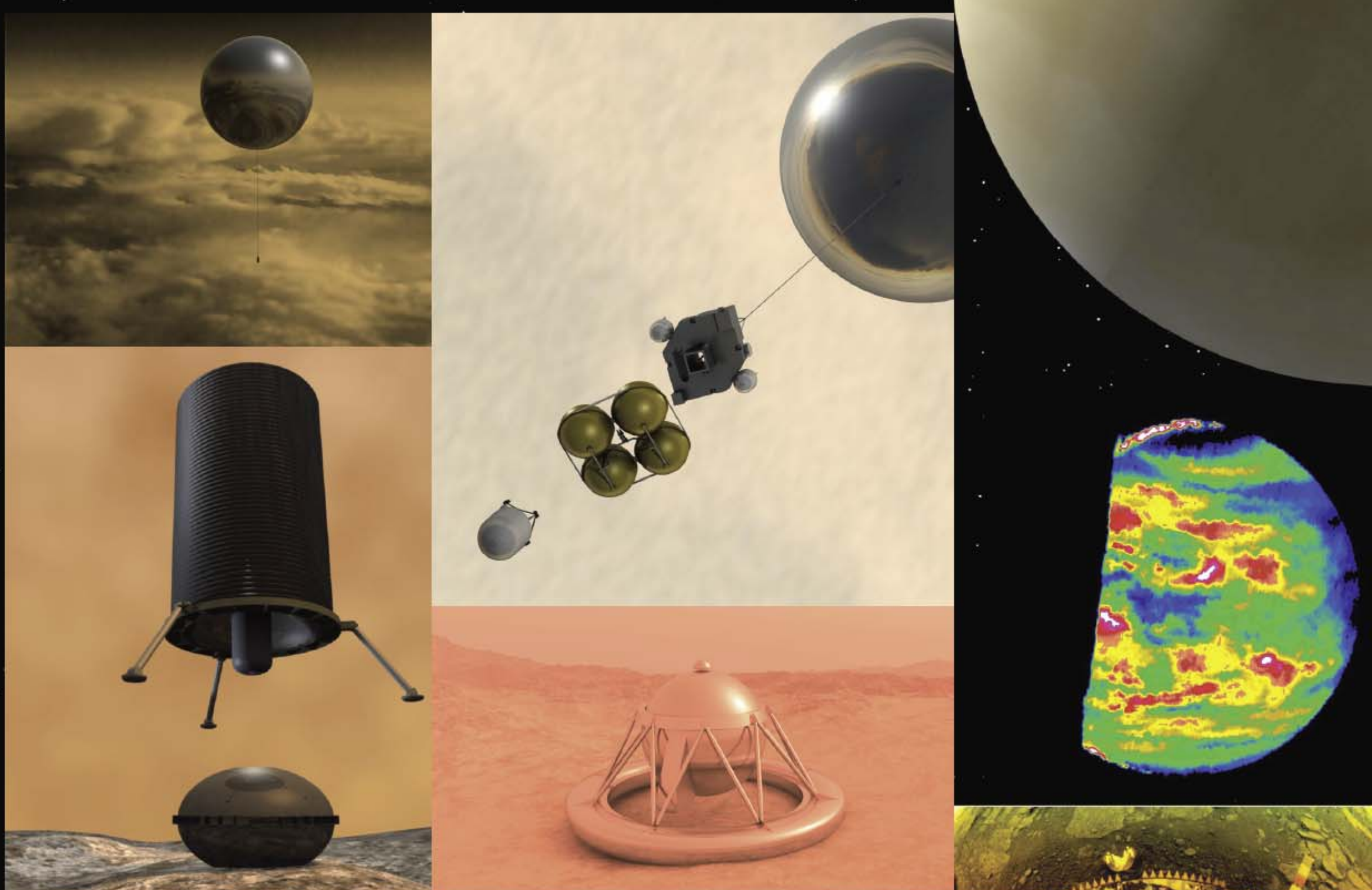
Venus Exploration Goals & Objectives



Venus Exploration Analysis Group (VEXAG)



VEXAG is NASA's community-based forum that provides science and technical assessment of Venus exploration for the next few decades. VEXAG is chartered by NASA Headquarters Science Mission Directorate's Planetary Science Division and reports its findings to both the division and to the Planetary Science Subcommittee of the NASA Advisory Council. VEXAG, which is open to all interested scientists and engineers, regularly evaluates Venus exploration goals, objectives, investigations, and priorities on the basis of the widest possible community outreach.

http://www.lpi.usra.edu/vexag

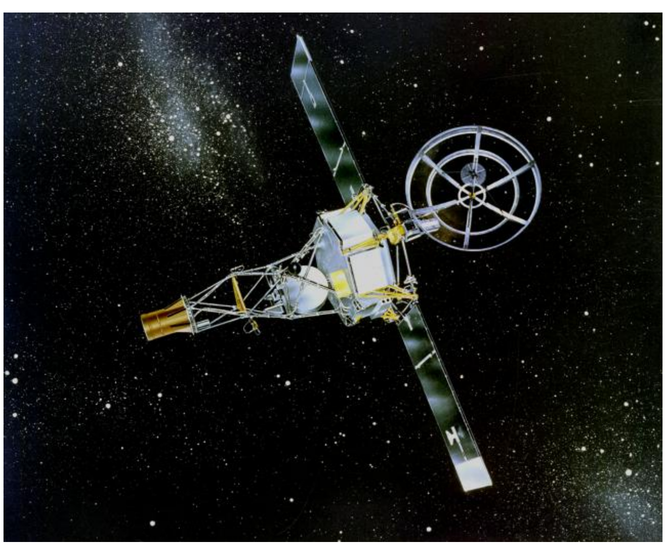
Front cover collage prepared by Tibor Balint

VENUS EXPLORATION GOALS AND OBJECTIVES
VENUS EXPLORATION ANALYSIS GROUP (VEXAG)

MARCH 2012

This 2012 edition and its predecessors—*VEXAG Goals, Objectives, Investigations, and Priorities* and *Pathways for Venus Exploration: October 2009*—were developed to provide information for Venus exploration needs. It is a living document, with revisions on an as-needed basis to capture the consensus views of the Venus community. From the first edition in November 2007 through February 2009 (VEXAG Meetings 4–6), modest updates were made to the document. The October 2009 edition had updates based on a Venus Flagship Science and Technology Definition Team Study, as well as the white papers submitted for the Planetary Science Decadal Survey. In 2011, the document was significantly revised and retitled in preparation for discussion at VEXAG Meeting #9 in late August 2011. This 2012 edition incorporates changes from the VEXAG Meeting #9 and has been prepared for distribution at the Venus Town Hall meeting, Lunar and Planetary Science Conference on March 21, 2012. A *Venus Exploration Themes* document was prepared as an adjunct to the 2011 editions to preserve important extracts from the October 2009 *Venus Exploration Pathways* document.

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



Artist's concept of Mariner 2, the first spacecraft to visit Venus (1962)

ACKNOWLEDGMENT

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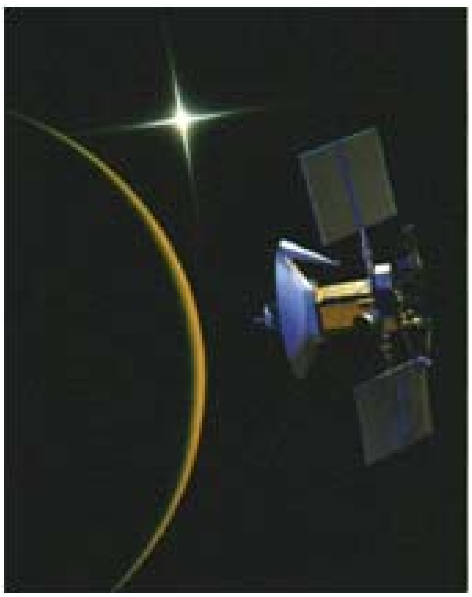


Artist's concept of Magellan spacecraft at Venus (1990–1994)

FOREWORD

This version of VEXAG's *Venus Exploration Goals and Objectives* was distributed at VEXAG Meeting #9 for review by the Venus community.

Since the October 2009 release *Pathways for Venus Exploration*, the Planetary Science Decadal Survey [sponsored by the National Research Council (NRC) and NASA] has been released as a Prepublication Copy titled *Vision and Voyages for Planetary Science in the Decade 2013–2022* [1], Akatsuki/Venus Climate Orbiter failed to enter into orbit around Venus in December 2010, and ESA's Venus Express mission has been authorized through December 2014 to continue operations. Subsequently, results of both the New Frontiers-3 and the Discovery-12 opportunities were announced in June 2011, in which no Venus missions were selected.

The Decadal Survey has recommended Venus as a high-priority target for exploration. The Venus In Situ Explorer (VISE) is one of five New Frontiers missions recommended for the next call, expected in ~2015. The Decadal Survey also finds that very valuable science can be carried out in the Discovery program, with the next call anticipated in 2013. The Venus Climate Mission is proposed as a large mission, in the queue after three other missions. The Flagship mission queue will be evaluated with respect to available resources. In the current constrained budget environment, the Venus Climate Mission appears to have the best likelihood of being realized through international coordination/participation by lowering the cost to NASA.

This edition of VEXAG's *Pathways for Venus Exploration*—now titled *Venus Exploration Goals and Objectives*—was revised to reflect these outcomes and the current and anticipated near future constrained budgets for exploration. The coming decade is critical for Venus exploration. The intent is to update the goals, objectives, and investigations, as needed, in future VEXAG meetings and through VEXAG focus groups.

Section 1 provides Venus goals, objectives, and investigations, which were refined by the Venus Science and Technology Definition Team (STDT) during their development of the Venus Flagship mission concept in 2008–2009 and as documented in a Venus white paper for the Planetary Science Decadal Survey. Section 2 provides the current VEXAG resolutions (formerly called Findings and Proposed Actions), which were developed at VEXAG Meeting #9 in August 2011. Possible missions to accomplish these goals are discussed in Section 3. The recommended Venus Climate Mission and two other mission concepts considered by the Inner Planets Panel of the Decadal Survey are summarized. Appendix A presents a discussion on why we should explore Venus now. Appendix B is an overview of current and future Venus missions. Appendix C describes new laboratory measurements needed to maximize the science return from current and future Venus missions. Appendix D is a collection of fact sheets for Decadal Survey Venus Climate Mission, Venus Intrepid Tessera Lander, Venus Mobile Explorer, and Venus Flagship Design Reference Mission.

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 the document.

1.1. Why Venus Now?

Venus proximity to Earth and its similarity in size and bulk density have earned it the title of "Earth's twin." The lack of seasons and oceans to help transport heat and momentum suggest that the Venusian 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 Venusian 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 kilometer 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 in 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 Venusian 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. 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 Venusian 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 Venusian 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 ºC, precluding the presence of liquid water. The Venusian highlands are mantled by deposits of an electrically conductive or semiconductive material.

The Venusian 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.
3. Characterize the current rates and styles of volcanism and tectonism, and how they have varied over time.
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.
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 Venusian 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 Venusian 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, and isotopes.
		Characterize the chemical compositions of materials near the Venusian 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, and mineral grain relationships) and 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 kilometers.
		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 Venusian 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 super-rotation through measurements of global-horizontal winds over several Venusian 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, Sn, HCl, HF, SO_3, ClO_2 and Cl_2), greenhouse gases, H_2O, and other condensables, in order to characterize sources of chemical disequilibrium in the atmosphere.
		Determine rates of gas exchange between the interior, surface and atmosphere.

2. VEXAG Meeting #9 Resolutions

This set of VEXAG resolutions (formerly called Findings and Proposed Actions) was updated at VEXAG Meeting #9 (August 30–31, 2011, Chantilly, Virginia).

1. VEXAG fully supports the Venus Climate Mission recommended by the Decadal Study, and urges the Planetary Science Division (PSD) to fund a Science Definition Study as soon as practical. As one aspect of the study, VEXAG urges that opportunities for meaningful international cooperation be explored to help to significantly reduce total mission cost to NASA.
2. VEXAG recognizes the importance to support an interdisciplinary approach to study climate, and will continue to spearhead and support the Comparative Climatology Conference in 2012. VEXAG requests the support of NASA to endorse and convene this multidisciplinary approach to climate.
3. VEXAG recognizing the attrition of scientists that the Venus community is experiencing and has formed a "Young Scholar Focus Group" to promote and encourage a new generation of Venus scientists.
4. VEXAG recognizes the importance of Earth stratospheric balloons as viable platforms for planetary and Venus observations and requests NASA PSD to continue to fund such initiatives as part of the suborbital program.

Also during VEXAG Meeting #9, Dr. Waleed Abdalati, NASA Chief Scientist, asked for feedback on why it is important to explore Venus now. He also requested a summary of past meetings that made recommendations, their outcomes, and outstanding scientific questions from those efforts. Appendix A provides a brief overview of findings that emphasize the importance of exploring Venus now, with thanks to Kevin Baines (Jet Propulsion Laboratory and University of Wisconsin–Madison), Mark Bullock (Southwest Research Institute), David Grinspoon (Denver Museum of Nature and Science), Ajay Limaye (California Institute of Technology), Paul Menzel (University of Wisconsin–Madison) and other colleagues for valuable input and comments. VEXAG hopes that this is the beginning of a continuing dialog.

Artist's concept of lightening on Venus. Courtesy of ESA.

3. Venus Exploration Mission Opportunities

To understand how the exploration goals and objectives for Venus can be met, it is useful to examine the Venus missions described in the Planetary Science Decadal Survey [1]. In addition, we include the Venus Flagship mission identified in the 2008 Venus Science and Technology Definition Team (STDT) study [2].

3.1. Discovery, New Frontiers, and Flagship Missions

Planetary exploration is discussed in the Planetary Science Decadal Survey [1], which endorses NASA's missions to solar system bodies under three mission classes:

- The Discovery Program consists of PI-led smaller missions that provide opportunities for targeted investigations with relatively rapid flight missions.
- The New Frontiers Program consists of PI-led medium-class missions addressing specific strategic scientific investigations endorsed by the Planetary Science Decadal Survey.
- Flagship missions address high-priority investigations that are so challenging that they must be implemented with resources significantly larger than those allocated to Discovery Program or New Frontiers missions.

3.1.1. Discovery-Class Missions

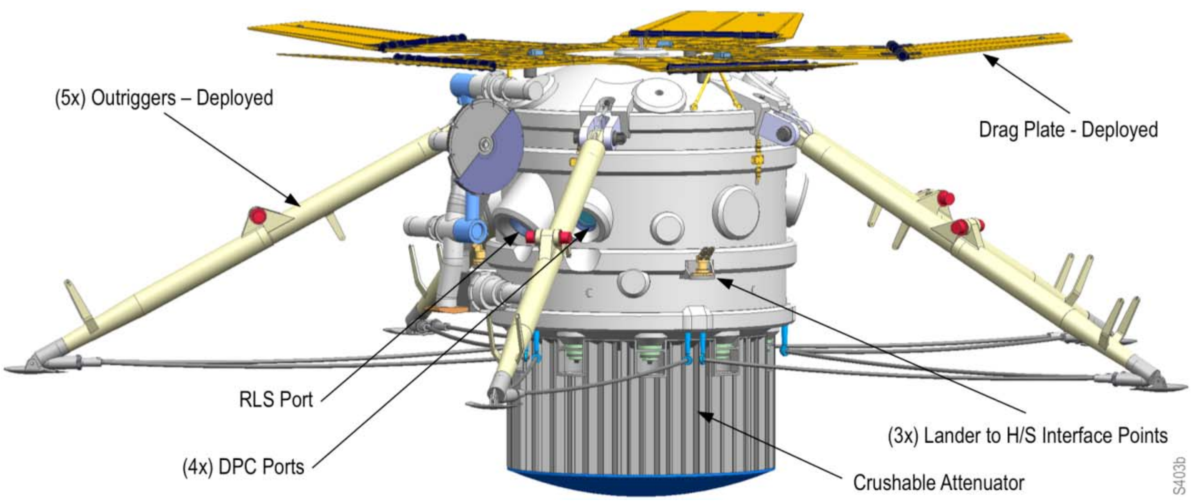
The Discovery Program, which began in the early 1990s, consists of PI-led missions that address targeted investigations with relatively rapid missions. Eleven full missions and five missions of opportunity (instruments and investigations flown on a non-NASA spacecraft as well as extended missions for NASA spacecraft) have been selected to date. The Discovery program is open to proposals for scientific investigations that address any area embraced by NASA's Solar System Exploration program, including the search for planetary systems around other stars. This provides an excellent means for tapping the creativity of the planetary science community. Details on these past and current missions can be found on the Discovery Program web site at http://discovery.nasa.gov/index.cfml.

Since the start of the Discovery Program, over a dozen proposals to explore Venus have been submitted. Seven proposals, including those to explore the atmosphere and geology of Venus, were submitted to the 2010 Discovery AO. Unfortunately, none were selected.

3.1.2. New Frontiers Missions: Venus In Situ Explorer (VISE)

The New Frontiers program comprises medium-class missions that address objectives identified by the Planetary Science Decadal Survey [1]. As Venus is considered to be Earth's sister planet, there is much to learn about Earth by studying Venus tectonics, volcanism, surface-atmospheric processes, atmospheric dynamics, and chemistry. The importance of the Venus In Situ Surface Exploration (VISE) mission was reaffirmed in the Planetary Science Decadal Survey [1] as a possible New Frontiers mission because many important questions about Venus cannot be obtained from orbit and thus require in situ investigations. The Surface and Atmospheric Geochemical Explorer (SAGE) was submitted in response to the 2009 New Frontiers AO to fulfill the VISE objectives. It was selected for a Step 1 concept study, but was not selected in the final evaluation. The science mission objectives for VISE as given in the Planetary Science Decadal Survey [1] are:

- Understand the physics and chemistry of the Venusian atmosphere, especially the abundances of its trace gases, sulfur, light stable isotopes, and noble gas isotopes.
- Constrain the coupling of thermochemical, photochemical, and dynamical processes in the Venusian atmosphere and between the surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles.
- Understand the physics and chemistry of the Venusian crust.
- Understand the properties of the Venusian atmosphere down to the surface and improve our understanding of Venusian zonal cloud-level winds.
- Understand the weathering environment of the crust of Venus in the context of the dynamics of the atmosphere and the composition and texture of its surface materials.
- Search for planetary-scale evidence of past hydrological cycles, oceans, and life and for constraints on the evolution of the atmosphere of Venus.



Artist's concept of the Surface and Atmosphere Geophysical Explorer (SAGE) lander, a mission proposed to New Frontiers-2 and New Frontiers-3 as Venus In Situ Explorer (VISE).

3.2. Venus Flagship-Class Missions

Certain high-priority investigations are so challenging that they cannot be achieved within the resources allocated to the Discovery and New Frontiers programs. With costs larger than those of New Frontiers missions, Flagship missions represent major national investments that must be strategically selected and implemented. Examples include comprehensive studies of planetary bodies, such as those undertaken by Voyager, Galileo, Cassini, and the Mars rovers. Thus, Flagship missions conduct in-depth studies of solar system bodies as well as sample return from planetary surfaces. These missions generally require large propulsion systems and launch vehicles. In addition, Flagship missions often require significant focused technology development prior to mission start, extended engineering developments, and extensive pre-decisional trade studies to determine the proper balance of cost, risk, and science return.

In 2009 NASA commissioned a Venus Flagship Mission Study (Venus Flagship Design Reference Mission) just prior to the Decadal Survey. In the worsening budgetary prospects, this mission was deemed too ambitious and expensive. The Venus Climate Mission recommended by the Planetary Sciences Decadal Survey [1] is a scaled-down version of the studied mission. In addition, the Inner Planets panel undertook studies of two focused missions—the Venus Intrepid Tessera Lander (VITaL) and a Venus Mobile Explorer (VME). The Venera-D mission is being studied for a 2016–2018 launch and is also a large-class mission similar to the Venus Flagship Design Reference Mission. These concepts are described briefly below.

3.2.1. Venus Climate Mission

The Planetary Sciences Decadal Survey [1] recommended a Venus Climate Mission (VCM)—a Flagship mission that will greatly improve our understanding of the current state and dynamics/evolution of the strong carbon dioxide greenhouse climate of Venus, thus providing fundamental advances in the understanding of and ability to model climate and global change on Earth-like planets. While the New Frontiers Venus In Situ Explorer (VISE) mission focuses on the detailed characterization of the surface, deep atmosphere and their interaction, VCM provides three-dimensional constraints on the chemistry and physics of the middle and upper atmosphere in order to identify the fundamental climate drivers on Venus. The VCM objectives would be accomplished through in situ observations, coupled with simultaneous measurements in the Venusian atmosphere. The principal scientific objectives of VCM would be to characterize the strong carbon dioxide greenhouse atmosphere of Venus, including variability over longitude, solar zenith angle, altitude and time of the radiative balance, cloud properties, dynamics and chemistry of the Venusian atmosphere. In particular:

- Characterize the strong CO_2 greenhouse atmosphere of Venus.
- Characterize the dynamics and variability of the Venusian super-rotating atmosphere.
- Characterize surface/atmosphere chemical exchange in the lower atmosphere.
- Search for atmospheric evidence of climate change on Venus.
- Determine the origin of the Venusian atmosphere as well as the sources and sinks driving evolution of atmosphere.
- Understand implications of the Venusian climate evolution for the long-term fate of Earth.

To accomplish these objectives, VCM would conduct synergistic observations from an orbiter, a balloon, a mini-probe, and two drop sondes. This would enable the first truly global 3-dimensional (and to a large extent 4-dimensional, via many measurements of temporal changes) characterization of the Venusian atmosphere. The mission would return a dataset on Venus radiation balance, atmospheric motions, cloud physics, and atmospheric chemistry and composition. The relationships and feedbacks among these parameters, such as cloud properties and radiation balance, address the most vexing problems that currently limit the forecasting capability of terrestrial GCMs. Evidence will also be gathered for the existence, nature and timing of a suspected ancient radical global change from habitable, Earth-like conditions to the current hostile runaway greenhouse climate. This would improve our understanding of the stability of climate and our ability to predict and model climate change on Earth and on extra-solar terrestrial planets. This mission would not require extensive technology development, and could be accomplished in the coming decade, providing extremely valuable data to improve our understanding of climate on the terrestrial planets.

VCM would be implemented via a carrier spacecraft, which would carry two drop sondes, mini-probe, and gondola/balloon system to Venus. The carrier spacecraft would provide telecommunications relay once the drop sondes, mini-probe, and gondola/balloon were deployed and then would conduct visible and IR monitoring of the Venusian atmosphere. The drop sondes and mini-probe would measure atmospheric constituents during a 45-minute descent from 55 km to the surface. The gondola/balloon system would conduct a 21-day atmosphere-monitoring campaign at 55 km. Instrumentation would be:

- Carrier Spacecraft
  - Venus Monitoring Camera, at visual and IR wavelengths
- Gondola/Balloon System
  - Neutral Mass Spectrometer
  - Tunable Laser Spectrometer
  - Atmospheric Structure Instrumentation
  - Nephelometer
  - Net Flux Radiometer
- Mini-Probe
  - Neutral Mass Spectrometer; Net Flux Radiometer; Atmospheric Structure Instrumentation
- Drop Sondes
  - Atmospheric Structure Instrumentation and Net Flux Radiometer

3.2.2. Venus Intrepid Tessera Lander (VITaL)

The VITaL mission concept provides key surface chemistry and mineralogy measurements in a tessera region as well as measurements of important atmospheric species that can answer fundamental questions about the evolution of Venus. The ability to characterize the surface composition and mineralogy within the unexplored Venus highlands would provide essential new constraints on the origin of crustal material and the history of water in Venus past. VITaL also would provide new high–spatial resolution images of the surface at visible and/or near infrared (NIR) wavelengths from three vantage points: on descent (nadir view), and two from the surface (panoramic view and contextual images of the linear surface chemistry survey). These data would provide insight into the processes that have contributed to the evolution of the surface of Venus. The science objectives could be achieved by a nominal payload that measures elemental chemistry and mineralogy at the surface, images surface morphology and texture on descent and after landing, conducts in situ measurements of noble and trace gases in the atmosphere, measures physical attributes of the atmosphere, and detects potential signatures of a crustal dipole magnetic field. A fact sheet is available in Appendix D. The study report is available at the VEXAG website <http://www.lpi.usra.edu/vexag/>.

3.2.3. Venus Mobile Explorer (VME)

The VME mission concept affords unique science opportunities and vantage points not previously attainable at Venus. The ability to characterize the surface composition and mineralogy in two locations within the Venusian highlands (or volcanic regions) would provide essential new constraints on the origin of crustal material, the history of water in the Venusian past, and the variability of the surface composition within the unexplored Venusian highlands. As the VME floats (~3 km above the surface) between the two surface locations, it could offer new, high–spatial resolution views of the surface at near-infrared (IR) wavelengths. These data would provide insights into the processes that have contributed to the evolution of the Venusian surface. The science objectives could be achieved by a nominal payload that conducts in situ measurements of noble and trace gases in the atmosphere, conducts elemental chemistry and mineralogy at two surface locations separated by ~8–16 km, images the surface on descent and along the airborne traverse connecting the two surface locations, measures physical attributes of the atmosphere, and detects potential signatures of a crustal dipole magnetic field. The VME study report can be found at the VEXAG website <http://www.lpi.usra.edu/vexag/> under Mission Concepts. A fact sheet is given in Appendix D.

3.2.4. Venus Flagship Design Reference Mission

NASA Headquarters conducted a Venus Flagship mission study in 2008–2009 based on recommendations identified by the 2003 NRC Decadal Survey [3] and the 2006 NASA Solar System Exploration Roadmap [4]. This study was supported by a NASA-appointed Venus Science and Technology Definition Team (STDT), an international group of scientists and engineers from France, Germany, Japan, the Netherlands, Russia, and the United States. JPL supported this study with a dedicated engineering team and the Advanced Project Design Team (Team X). The STDT assessed Venus science goals and investigations, leading to the Venus Flagship Design Reference Mission (VFDRM)—which includes a notional instrument payload, subsystems, and technologies—implemented using an orbiter, balloons, and landers (Figure 3-1 and Appendix D). Although VFDRM is proposed as a single large flagship mission, some of its objectives can be achieved through smaller New Frontiers and Discovery missions.

NASA guidelines for this study specified a launch between 2020 and 2025 with the total mission cost being $3B to $4B. Although the study assumed no international contributions, it is expected that a future NASA Venus flagship mission would, in fact, be conducted with international collaboration. This mission would revolutionize our understanding of the climate of terrestrial planets (including the coupling between volcanism, tectonism, the interior, and the atmosphere); the habitability of planets; and the geologic history of Venus (including the existence of a past ocean).

Although VFDRM is proposed as a single large flagship mission, some of its objectives can be achieved through smaller missions, while other objectives are accomplished through coordinated and/or concurrent observations.

This mission is designed to address top-level science questions:

- Is Venus geologically active today?
- How does the Venusian atmospheric greenhouse work?

- What does the surface say about Venusian geological history?
- How does the Venusian atmospheric super-rotation work?
- How do the surface and atmosphere interact to affect their compositions?
- How are the clouds formed and maintained?
- How is sunlight absorbed in the Venusian atmosphere?
- What atmospheric loss mechanisms are currently at work?
- What kind of basalts make up Venusian lava flows?
- Are there evolved, continental-like rocks on Venus?
- How is heat transported in the mantle, and how thick is the thermal lithosphere?
- What happened on Venus to erase 80% of its geologic history?
- Did Venus ever have oceans and, if so, for how long?
- Did the early atmosphere of Venus experience catastrophic loss, either due to hydrodynamic escape or a large impact?
- Did Venus have a magnetic field, and does it have a remnant one now?

These questions translate to three major themes:

- ***What Does the*** Venusian ***Greenhouse Tell Us About Climate Change?*** Addressed by characterizing the dynamics, chemical cycles, and radiative balance of the Venusian atmosphere and by placing constraints on the evolution of the Venusian atmosphere.
- ***How Active is Venus?*** Addressed by identifying evidence for active tectonism and volcanism in order to place constraints on evolution of tectonic and volcanic styles, characterizing the structure and dynamics of the interior in order to place constraints on resurfacing, and by placing constraints on stratigraphy, resurfacing, and other geologic processes.
- ***When and Where Did the Water Go?*** Addressed by identifying evidence of past environmental conditions, including oceans, and characterizing geologic units in terms of chemical and mineralogical composition of the surface rocks in context of past and present environmental conditions.

The notional flagship mission to address these questions, the Venus Flagship Design Reference Mission, consists of two launched spacecraft, one being an orbiter and the other delivering two entry vehicles, where each entry vehicle carries dual landers and balloons (Figure 3-1). In this dual-launch scenario, two Atlas V launches are needed to send these spacecraft to Venus. The first launch vehicle would deliver the two landers and the two balloons to Venus on a Type-IV trajectory. The second launch vehicle would deliver the orbiter on a Type-II trajectory to Venus. The orbiter would arrive at Venus first, with sufficient time for checkout and orbit phasing before the landers and balloons arrive 3.5 months later. The orbiter would support two functions. First, it would act as a telecommunication relay to transmit data to/from the landers and balloons to Earth during the in situ observations. Once the landers and balloons complete their observations, the orbiter would transition from its telecom relay phase to an orbital science phase with a 2-year remote sensing mission. The landers would be designed for a 1-hour atmospheric descent followed by 5 hours of operation on the surface. The balloons and their payloads would be designed to operate for 1 month at an altitude of 55 km, circumnavigating the planet several times, while gradually drifting from mid latitudes towards the polar vortex.

VFDRM can be implemented with modest technology developments, such as those for sample acquisition and handling; aerial mobility; and high temperature–tolerant components (e.g., sensors, electronics, mechanisms, instruments, and power storage). This mission also lends itself to spinoffs, as various elements could be implemented as precursor Discovery or New Frontiers missions. Continuation of this flagship mission study would further refine science objectives, and technology development planning based on technology needs for this and other missions requiring long-lived mission elements. Appendix D includes the fact sheet for NASA's Flagship Mission to Venus.

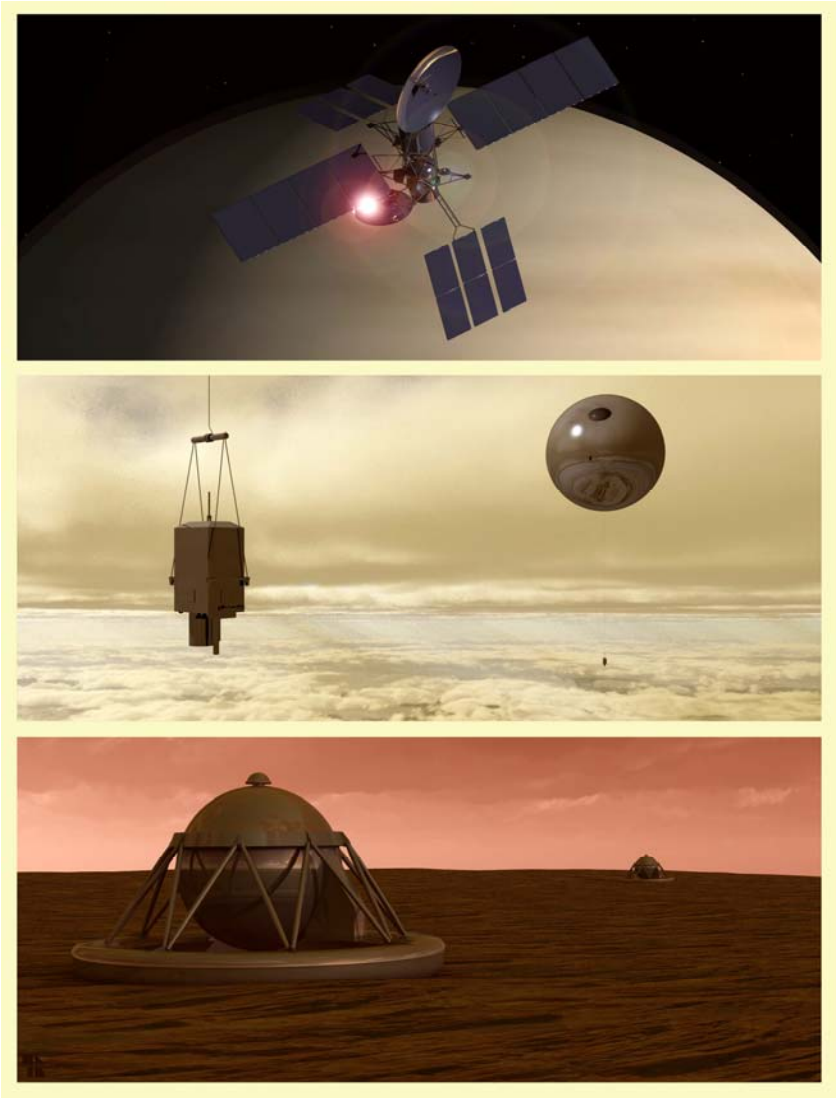


Figure 3-1. Artist's concept of Venus flagship orbiter, balloons, and landers—elements of the Venus Flagship Design Reference Mission, developed by the Venus STDT in 2008–2009. Artwork by Tibor Balint.

4. References and White Papers for Next Decadal Survey

[1] National Research Council of the National Academies, Committee on the Planetary Science Decadal Survey Space Studies Board Division on Engineering and Physical Sciences, *Visions and Voyages for Planetary Science 2013–2022*: http://solarsystem.nasa.gov/multimedia/download-detail.cfm?DL_ID=742

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

[3] 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

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

Most of these reports can be accessed via the Reports section of VEXAG website <http://www.lpi.usra.edu/vexag/>.

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Treiman, A., et al., Report on the LPI Workshop: "Venus Geochemistry: Progress, Prospects, and Future Missions," April 2009, http://www.lpi.usra.edu/vexag/

Venus Express: Results of the Nominal Mission, *JGR* Special Issues, Volume 114, Numbers E5 and E9, 2009.

"Advances in Venus Science," *ICARUS* special issue, to be published in Fall 2011.

Towards understanding the climate of Venus: Application of terrestrial models to our sister planet, to be published by the International Space Science Institute, Bern, Switzerland Fall 2011.

Venus White Papers for the Planetary Science Decadal Survey

"Venus Exploration Goals, Objectives, Investigations, and Priorities," *Sanjay Limaye, Suzanne Smrekar, and VEXAG Executive Committee*

"Venus Atmosphere: Major Questions and Required Observations," *Sanjay Limaye, Mark Allen, Sushil Atreya, Kevin H. Baines, et al.*

"Venus: Constraining Crustal Evolution from Orbit Via High-Resolution Geophysical and Geological Reconnaissance," *James Garvin, Lori Glaze, Sushil Atreya, Bruce Campbell, Don Campbell, Peter Ford, Walter Kiefer, Frank Lemoine, Greg Neumann, Roger Phillips, Keith Raney*

"Comparative Planetary Climate Studies," *David Grinspoon, Mark Bullock, et al.*

"Venus Geochemistry: Progress, Prospects, and Future Missions," *Allan Treiman, David Draper, M. Darby Dyar*

"Previously Overlooked/Ignored Electronic Charge Carriers in Rocks," *Friedemann Freund*

"Mission Concept: Venus in situ Explorer (VISE)," *Larry W. Esposito and the SAGE Proposal Team*

"Venus Atmospheric Explorer New Frontiers Mission Concept," *Kevin Baines, Sushil Atreya, Tibor Balint, Mark Bullock, et al.*

"The Venus Science and Technology Definition Team Flagship Mission Study," *Mark Bullock, David Senske, et al.*

"Technologies for Future Venus Exploration," *Tibor Balint, James Cutts, Mark Bullock, et al.*

"Thermal Protection System Technologies for Enabling Future Venus Exploration," *Ethiraj Venkatapathy et al.*

All of these white papers can be accessed via the White Papers section of VEXAG website <http://www.lpi.usra.edu/vexag/>.

Artist's concept of Pioneer Venus Orbiter (1978–1992)

5. VEXAG Executive Committee Overview

NASA's Science Mission Directorate established the community-based Venus Exploration Analysis Group (VEXAG) in July 2005 to provide scientific and technical assessments for the exploration of Venus. VEXAG reports its findings to NASA and to the Planetary Science Subcommittee of the NASA Advisory Council. VEXAG is currently composed of two co-chairs, an ex officio from NASA Headquarters, and an executive committee. Focus groups are formed as needed to address specific questions. Each focus group includes scientists, technology experts, NASA representatives, international partner representatives, and a VEXAG chair.

VEXAG Co-Chairs and Ex Officio

VEXAG Co-chairs: Sanjay Limaye (sanjayl@ssec.wisc.edu), University of Wisconsin, Madison, Wisconsin and Suzanne Smrekar (Suzanne.E.Smrekar@jpl.nasa.gov), Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California

Adriana Ocampo (adriana.c.ocampo@nasa.gov), Ex Officio, Venus Program Executive, NASA Headquarters, Washington D.C.

VEXAG Focus Groups

At VEXAG Meeting #9 in August 2011, the previous focus groups were closed out and five new focus groups were created. These new focus groups (in alphabetical order) are:

Competed Missions and ROSES Focus Group–Lori Glaze (lori.s.glaze@nasa.gov), Goddard Space Flight Center, Lead

International Venus Exploration Working Group–Mark Bullock (bullock@boulder.swri.edu), Southwest Research Institute, Lead

Technology Development and Laboratory Measurements Focus Group– Pat Beauchamp (Patricia.M.Beauchamp@jpl.nasa.gov), JPL, and Tibor Kremic (tibor.kremic@nasa.gov), Glenn Research Center, Co-Leads

Venus Goals and Objectives (Document) and Venus Exploration Sites Focus Group–Buck Sharpton (sharpton@lpi.usra.edu), Lunar and Planetary Institute, Lead

Young Scholars Focus Group–Stephanie Johnston (planetarygirl@gmail.com), University of Maryland, and Danielle Piskorz (dpiskorz@mit.edu), Massachusetts Institute of Technology/Carnegie Institute, Co-Leads

VEXAG Executive Secretary

Tommy Thompson (thomas.w.thompson@jpl.nasa.gov), JPL, Pasadena, California

VEXAG Web Master

Ronna Hurd (rhurd@hou.usra.edu), Lunar and Planetary Institute, Houston, Texas

Past VEXAG Co-Chairs

2005 until November 2007

Janet Luhmann (jgluhmann@ssl.berkeley.edu), University of California, Berkeley, California

Sushil Atreya (atreya@umich.edu), University of Michigan, Ann Arbor, Michigan

November 2007 until Spring 2009

Ellen Stofan (ellen@proxemy.com), Proxemy, Inc.

6. Acronyms and Abbreviations

ASPERA	Venus Express fields and particles experiment
CCD	charge-coupled device
ESA	European Space Agency
IR1 and IR2	Akatsuki's infrared cameras
JAXA	Japanese Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LAC	Akatsuki's Lightening and Airglow Camera
LIR	Akatsuki's long wavelength infrared camera
LPI	Lunar and Planetary Institute
MAG	Venus Express magnetometer experiment
NASA	National Aeronautics and Space Administration
PSD	NASA Planetary Science Division
ROSES	Research Opportunities in Space and Earth Sciences
RS	Akatsuki's Radio Science experiment
SPICAV–SOIR	Venus Express infrared and ultraviolet imaging spectrometer
STDT	Science and Technology Definition Team
UVI	Akatsuki's ultraviolet imager
VCM	Venus Climate Mission
Vega	Russian Halley/Venus Lander and Orbiter Mission
VeRa	Venus Express radio science experiment
VEXAG	Venus Exploration Analysis Group
VFDRM	Venus Flagship Design Reference Mission
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer (Venus Express)
VISE	Venus In Situ Explorer
VITaL	Venus Intrepid Tessera Lander
VMC	Venus Monitoring Camera (Venus Express)
VME	Venus Mobile Explorer

APPENDIX A. WHY EXPLORE VENUS NOW?

During the 9th VEXAG (August 30 – 31, 2011, Chantilly, Virginia) Dr. Waleed Abdalati, NASA Chief Scientist, asked for some feedback on why Venus is important to explore now. He also requested a summary of past meetings that made recommendations, their outcomes, and outstanding scientific questions from those efforts. Below is a brief overview of findings that emphasize the importance of exploring Venus now, with thanks to Kevin Baines (JPL/UW- Madison), Mark Bullock (SwRI), David Grinspoon (DNMS), Ajay Limaye (CalTech), Paul Menzel (UW-Madison) and other colleagues for valuable input and comments. VEXAG hopes that this is the beginning of a continuing dialog.

4 November 2011 — *Sanjay S. Limaye, VEXAG Chair*

Introduction

2011 marks the 250th anniversary of the discovery of the atmosphere of Venus by Lomonosov (Marov, 2004) and half a century since the high surface temperature was proposed by Sagan (1960) to arise from a runaway greenhouse effect. Since then, Venus continues to be a suitable natural laboratory to enhance our understanding of Earth's atmospheric processes and future climates. Similar to the Earth in size and many physical properties, Venus presents a simpler atmosphere to model – no seasons by virtue of its rotational axis being nearly perpendicular to its orbital plane, nearly spherical with much smaller elevation differences, no hydrologic cycle and a global cloud cover. Yet there are key differences which can illuminate the role of a variety of climatic processes. The upper clouds contain a variable amount of an unknown ultraviolet absorber which is responsible for a major fraction of the solar energy being absorbed in the upper atmosphere some 55 km above the surface. With a surface pressure of over 90 bars from a 95% carbon dioxide and 3% nitrogen atmosphere with traces of water vapor, sulfuric acid, carbon monoxide and other molecules, Venus presents an extreme case of the role of the greenhouse effect on global warming. Another key difference between Venus and Earth is the rotation rate – Venus rotates backward, at a rate 243 times slower than the spin of the Earth, which in turn both lengthens the solar day and reduces the Coriolis force by two orders of magnitude. Why it spins backwards is an anomaly whose origins are not understood at all, but the impact on atmospheric circulation and climate is significant. Studying how our neighboring planet operates under a significantly different set of environmental conditions enables a better understanding of the planetary atmospheres in general and Earth in particular. Venus presents an atmosphere with a wide range of dynamical and radiative heating time constants (Stone, 1975), and our inability to apply the models with the same basic physics strongly suggests that the parameterization schemes are not applicable to the wider range of conditions encountered. Venus presents opportunities for "stress" tests of the climate models with significant increases in greenhouse gases which will boost the confidence in predictions Earth's future climate.

Time and again, studying Venus has resulted in revolutionary changes to our thinking about Earth. The first glimpse of the depths of Venus by the very first interplanetary spacecraft, Mariner 2 in 1962, revealed an unexpectedly hot atmosphere 200 K warmer than predicted, thus revealing the importance of the greenhouse effect in determining planetary climates. As well, the role of CFC (chlorofluorocarbons) in ozone chemistry - so important in explaining the ozone hole in the Earth's southern polar atmosphere - was discovered by Venus scientists to explain the chemistry of chlorine and other trace molecules in Venus' upper atmosphere. The recent discovery of an ozone layer (and other species) in Venus' atmosphere by ESA's Venus Express orbiter provides an opportunity for comparative atmospheric studies. As a another example, a widely accepted mechanism for the demise of the dinosaurs on Earth was the development of a decade-long, globe-girdling Venusian-style sulfuric acid cloud layer resulting from the impact of a bolide in the Yucatan peninsula some 65 million years ago, which resulted in a dramatic cooling at the Earth's surface. The enhanced CO_2 content due to extensive fires generated by the impact then warmed the planet to historically high temperatures. Both of these severe climatic results of the dinosaur-killing impact stemmed directly from Venus studies.

As earlier missions to Venus have taught us about the nature of Earth's environment and climate, so too will future explorations.

Background

In "**Discovery of Global Warming**" Spencer Weart (www.aip.org/history/climate/index.htm) writes:

> *"In the 1960s and 1970s, observations of Mars and Venus showed that planets that seemed much like the Earth could have frightfully different atmospheres. The greenhouse effect had made Venus a furnace, while lack of*

atmosphere had locked Mars in a deep freeze. This was visible evidence that climate can be delicately balanced, so that a planet's atmosphere could flip from a livable state to a deadly one.

A planet is not a lump in the laboratory that scientists can subject to different pressures and radiations, comparing how it reacts to this or that. We have only one Earth, and that makes climate science difficult. To be sure, we can learn a lot by studying how past climates were different from the present one. And observing how the climate changes in reaction to humanity's "large scale geophysical experiment" of emitting greenhouse gases may teach us a great deal. But these are limited comparisons — different breeds of cat, but still cats. Fortunately our solar system contains wholly other species, planets with radically different atmospheres."

Further, he writes:

"Could study of these strange atmospheres provide, by comparison, insights into the Earth's weather and climate? With this ambitious hope Harry Wexler, head of the U.S. Weather Bureau, instigated a "Project on Planetary Atmospheres" in 1948. Several leading scientists joined the interdisciplinary effort. But the other planets were so unlike the Earth, and information about their atmospheres was so minimal, that the scientists could reach no general conclusions about climate. The project was mostly canceled in 1952" (Doel, 1966).

Fortunately, during the last fifty years the situation has improved dramatically. Spacecraft exploration of Venus over the last half century (beginning with Mariner 2's fly-by in 1962 up to the current monitoring by ESA's Venus Express) has revealed the similarities and differences between Earth and Venus. How these two planets evolved so differently remains the fundamental question where the answer will greatly enhance our understanding of Earth's future climate. The key questions that we still seek answers to include: How does Venus lose its heat? What happened to its inventory of water? Why doesn't Venus have plate tectonics? Why does it spin so slowly? What drives its superrotating atmosphere? Why is the thermospheric circulation so variable? Why doesn't Venus have a magnetic field? Answering these questions is critical to understanding the terrestrial planets rapidly being discovered around other stars by the Kepler and Corot missions from NASA and ESA and by ground based telescopes.

Since the 1980s, various NRC studies have highlighted the value of Venus exploration. In response, since the beginning of the Discovery Program in 1992, at least twenty four proposals for Venus missions have been submitted to seven Discovery proposal opportunities, with four of them being selected for the second round (Concept Study Report) . These missions have attempted to answer some of the most crucial questions noted by the first Decadal Surveys and earlier National Academy reports. Yet, none of them were selected for launch.

The 1988 NRC report noted that the goals of planetary exploration are met through observations and missions in which the levels of investigation are generally progressive. For geoscience studies through network science, sample return and surface meteorology, Venus was deemed to have the highest priority (NRC 1988). However, the report noted that "the high surface temperatures will make this mission very difficult". The report, published before Magellan data were obtained, nevertheless noted subsequent exploration (p. 107):

> *"In the case of Venus, a good map is partially in hand; completion is expected with the planned radar mapper mission (Magellan). Current lack of this map inhibits detailed projections for future missions. An initial set of geochemical and mapping information has been obtained from Soviet investigations. The hostile environment of the planet requires much more technological development for future missions than is the case for the other terrestrial planets. Nevertheless, the kind of geophysical and geochemical information desired from Venus is similar to that desired from the other terrestrial planets, and the means needed to acquire this will include probes, the establishment of a global network, and sample returns. Accomplishing these objectives will provide interesting technological challenges".*

The Report from the Workshop on Dynamics of Planetary Atmospheres (Suomi and Leovy, 1978) concluded that the observational goals for the Venus atmosphere are:

(1) To determine, more completely, the vertical and horizontal distributions of radiative heating and cooling, and the relationship of radiation fluxes to clouds,

(2) To define the mean atmospheric state, including the large-scale wind distribution,

(3) To define smaller scale and transient wind systems, and identify their mechanisms,

(4) To discover whether clues to past atmospheric processes are imprinted in the surface

The observations recommended were:

Composition of the atmosphere
Albedo and composition of the surface

Composition, microstructure, horizontal and vertical distribution of clouds and aerosols
Radiative flux divergence
Pressure and temperature as function of location and time
Winds as a function of location and time (*by direct measurement or by cloud motion analysis)*
High resolution radar imaging of the surface

The report further concluded:

> *"In addition to the opportunity to test the generality of physical parameterizations derived from terrestrial experience, under vastly different conditions, planetary science has already provided a number of examples in which the experience and skills developed in the study of other planets have accelerated progress in understanding of terrestrial problems. Speed in narrowing the uncertainties surrounding estimates of various earth climatic theories has become a clear need in view of such possible human influences on climate as the potential for alteration of the ozone layer or of changing the heat balance by increasing the CO_2 concentration. Research in both problem areas has already benefited from the existence of a planetary research program. For example, the study of the radiative properties of CO_2 for the conditions on Venus led to a parameterization of the CO_2 influence on radiation. Although originally intended for Venus application, this parameterization has subsequently been widely used for calculations in the earth's stratosphere. Undoubtedly, such a development would eventually have occurred for earth, but the existence of a scientific effort in planetary atmospheres speeded up the process considerably. In fact, much of radiative transfer theory now in common usage in earth applications was originally developed for extraterrestrial applications."*
>
> *As another example, one component of some earth climatic theories is the parameterization of horizontal and vertical heat fluxes as functions of the large-scale thermal forcing. Some of these theories which are at the core of highly parameterized earth climate models, were originally developed in the context of comparative planetary studies. The point is not that such parameterizations are necessarily "correct," or even "optimal," but they have generated controversy and have stimulated others to explore this problem…"*

The report summarized its findings by identifying two items:

(1) Simulation models and mechanistic models can be applied to other planets as well as to the Earth. If the actual circulations of the planetary atmospheres are known, this application provides a means of testing model performance under very different conditions. In so doing, this helps to validate use of the models to examine climate, when the external conditions governing climate are very different from those of the present.

(2) Many physical processes which occur in the Earth's atmosphere also occur in the atmospheres of other planets, but in a more extreme form. The study of planetary atmospheres helps us to gain a better fundamental understanding of such processes, and perhaps even to identify terrestrial processes which would otherwise be missed.

Hunten (1992) reviewed the Pioneer Venus results on the presence of water vapor on Venus, and proposed in "Lessons for Earth" that the model examining the greenhouse effect in a steam atmosphere on Earth as might result from increased carbon dioxide should also work on Venus. He noted that, "There is no likelihood that the Earth will actually come to resemble Venus, but Venus serves both as a warning that major environmental effects can flow from seemingly small causes, and as a test bed, for our predictive models of the Earth".

In a review article, Gierasch et al. (1997) noted:

> *The overall spin of "superrotation" of the Venus atmosphere is a striking phenomenon… But the fundamental cause of the global superrotation remains a mystery in spite of data from Earth-based observatories, from Pioneer Venus, from several Russian probes, from a Russian/French balloon experiment, and from the NASA Galileo flyby. The key missing knowledge is of momentum transfer processes in the deep atmosphere, between the surface and the cloud deck. Neither the forcing nor the drag and dissipation mechanisms are known. ... It is concluded that further measurements, in conjunction with numerical modeling, will be required to resolve this puzzling and challenging question. New data must improve by an order of magnitude on* the accuracies achieved by the Pioneer *Venus probes.*

Sample Mission Concepts for a Better Understanding of Venus

Crisp et al. (2002) provided arguments for exploring Venus to elucidate the divergent evolution of Earth-like planets. This paper represents the community input for the first Planetary Science Decadal Survey (2003 – 2013) conducted by the US National Academies at NASA's request. Crisp et al. presented a case for several missions:

- The Noble gas and Trace Gas Explorer is the highest priority mission because its data are vital to our understanding of the origin of Venus. This small mission requires a single entry probe that will carry the state-of-the-art instruments needed to complete the noble gas inventories between the cloud tops and the surface.
- The Global Geological Process Mapping Orbiter is a small to medium class mission. It will carry a C-and/or X-band radar designed for stereo or interferometric imaging, to provide global maps of the surface at horizontal resolutions of 25 to 50 meters. These data are needed to identify and characterize the geological processes that have shaped the Venus surface.

- The Atmospheric Composition Orbiter is a small mission that will carry remote sensing instruments for characterizing spatial and temporal variations in the clouds and trace gases throughout the atmosphere. This mission will collect the data needed to characterize the radiative, chemical, and dynamical processes that are maintaining the thermal structure and composition of the present atmosphere.
- The Atmospheric Dynamics Explorer is a small to medium mission that will deploy 12 to 24 long-lived balloons over a range of latitudes and levels of the Venus atmosphere to identify the mechanisms responsible for maintaining the atmospheric superrotation.
- The Surface and Interior Explore is a large mission that will deploy three or more long- lived landers on the Venus surface. Each lander will carry a seismometer for studies of the interior structure, as well as in-situ instruments for characterizing the surface mineralogy and elemental composition. This mission requires significant technology development.

From this community input, the 2003 Decadal Survey recommendations included a "Venus In Situ Explorer" as a candidate mission in the New Frontiers-2 Announcement of Opportunity. A proposal "Surface and Geochemistry Explorer (SAGE)" (Esposito 2011) was submitted in response to this AO but was not selected. The mid-term review of the progress on the NRC recommendations resulted in slightly modified language in the NOSSE Report (NRC 2008) for VISE in the New Frontiers-3 AO for which two candidate missions were proposed. The report noted that:

> *"In some cases those mission-specific recommendations introduce significant changes into the possible mission, notably in defining the parameters for the Venus In Situ Explorer and the Network Science missions. The committee noted that these science goals may not all be achievable in a single mission but believes that the choice and prioritization of goals are best left to those proposing and evaluating the missions. "*

Of these, SAGE was selected for Concept Study Report due by January 2011. The mission was not ultimately selected for flight by NASA (June 2011). The New Frontiers-4 AO will presumably receive additional proposals for Venus.

In the meantime, NASA also undertook a study of a flagship mission to Venus (Bullock et al., 2009), just prior to the 2011 Decadal Survey of Planetary Science. A scaled down version of this mission was recommended by this survey (Venus Climate Orbiter). The

Mars Express spare was sent to Venus by ESA in November 2005 to become the Venus Express orbiter, and JAXA launched Akatsuki/Venus Climate Orbiter in May 2010 which is now awaiting a second attempt at orbit insertion around Venus in 2015, having missed it the first time in December 2010. These and other missions proposed to Discovery Program remain hopes and dreams to obtain important new observations, but the time for NASA to explore Venus is now.

Modeling the Climate of Venus

The recent Decadal Survey (Visions and Voyages for Planetary Science in the Decade 2013-2022) summarized the outstanding questions about Venus. Some pertinent issues not addressed therein have to do with atmospheric modeling. Numerical models have been attempting to simulate Venus or Venus-like atmospheres through adaptations of Earth circulation models for the last several decades. Only in the last one or two decades have the models been able to produce superrotation using a very simplified approach. A Working Group on Climate Modeling of Venus (International Space Science Institute, Bern, Switzerland) compared results of current models using the same initial conditions, similar to what has been done with terrestrial models, and the results are not very re-assuring. While most of these are able to achieve "superrotation," they disagree on the details of the circulation in the deep atmosphere and in the mechanisms that support the superrotation (Lebonnois et al., 2011, Lewis et al., 2011). The subsolar to anti-solar circulation that was anticipated prior to the discovery of the superrotation of the Venus atmosphere has since been discovered in the thermosphere, but highly variable in the strength and even the direction of the flow in the 90-110 km layer above the surface. This variability also cannot be simulated and its causes are not yet understood (Limaye and Rengel, 2011). Similarly, the organization of the observed cloud level circulation in hemispheric vortices (Limaye et al., 2009) also cannot be simulated to probe its deeper structure, which is currently inaccessible through remote measurements.

Why is it so difficult to simulate the different aspects of the atmospheric and thermospheric circulation of Venus? It took many years for the Earth climate models to be "tuned" by tweaking the parameterization of key processes. That the high surface pressure and temperature should be such a great impediment to the successful numerical simulation of Venus' atmospheric circulation using some of the fastest computers available is one of the greatest frustrations of atmospheric science. The causes of this failure reside in imperfect parameterization of the radiative heating in the atmosphere and small scale processes. That the same processes are basic to the Earth climate models should give us a pause. The ultraviolet absorber on Venus plays a role very similar to the water vapor (and ozone to some degree) in Earth's atmosphere for deposition of energy above the surface but through different processes. Its global distribution is also similarly spatially and temporally highly variable. Unlike water vapor on Earth (mostly in the troposphere), however, the Venusian UV absorber also occurs far above the surface in the upper cloud layer (mesosphere). It certainly should boost confidence in long term projections of Earth's climate once we can successfully model Venus' atmospheric circulation. This is especially true as substantial increases in the carbon dioxide and water vapor are considered for Earth.

The warming that has been measured on Earth in recent decades has raised world-wide concern and has led to many independent climate modeling efforts (IPCC, 2007). The numerous models project a range of warming over the next decades, with some variation in the spatial details due to increased carbon dioxide. For the past several years, the US Department of Energy has organized an intercomparison of global climate models; an effort initiated and overseen by the World Climate Research Program, which started with the validation of atmospheric models. (Gates, 1992). Venus provides an opportunity for a "stress test" of such models as most attempts to realistically simulate the observed conditions use different Earth weather/climate models adapted for Venus physical conditions (Lebonnois et al., 2011). The inability of these models to agree upon the significant processes responsible for superrotation and the disagreement with available observations suggests that the "fine tuning" or parameterization of small scale processes and radiative heating may not be appropriate for Venus conditions. This raises the concern that the parameterization for large increases in the abundance of carbon dioxide in Earth's atmosphere should be examined. Venus provides an extreme case for such a test.

In the last few decades the discovery of life in extreme environments has led to a new concept of the habitable zone. As we look for life elsewhere, it is also important to remember that the Venus clouds present a potentially habitable environment for certain bacteria (Sagan, 1971; Schulze-Makuch and Irwin, 2002; Schulze-Makuch et al., 2004).

Although they commonly originate from the surface, bacteria have been found at high altitudes, including in cosmic dust samples (Yang et al., 2009); hence it would be worth testing the habitability of the Venus clouds. An experiment to make such observations was described at the 9the VEXAG meeting (Juanes-Vallejo, 2011).

Sun-Climate Connection on Venus and Earth

While the connection between the sun and climate is obvious, the response of the climate to the solar variability is complicated and not fully understood (Lean and Rind, 1996). The NASA Living With a Star Sun-Climate Task Group (J. Eddy, Chair) noted in its report (Eddy, 2003) "at this time we simply do not know whether longer-term climatically-significant variations in solar irradiance exist or don't exist. Nor do we know the magnitude of these conceivable changes". Much of the difficulty is due to the different time scales characteristic of the climate markers to the solar irradiance. Other difficulties arise in terms of the spectral variability of the irradiance over time along with the total solar irradiance. It is in this instance that Venus serves as a near-perfect natural laboratory – uniform cloud cover containing heterogeneous ultraviolet absorber(s) responsible for controlling the climate. Therefore, one should expect variability in the Venus cloud cover in response to the solar output. Measurements to monitor such changes from orbit are feasible and may be simpler to some degree than for Earth.

The data gap that hampered the effort in the late 1940's to simulate other atmospheres has now been significantly reduced, but not eliminated for Venus through the last few decades of spacecraft data from US, Soviet and European missions to Venus. Besides lending balance to the Planetary Science Division, exploration of Venus holds implications for extrasolar planets, the sun-Earth connection and habitability--all of topics of interest to the Earth Science,Heliophysics and Astrophysics Divisions of NASA/SMD. An effort comparative climatology of terrestrial planets by NASA/SMD is thus highly desirable.

Key questions about Venus have been discussed in VEXAG meetings and presented in its Goals and Objective document which is periodically updated (www.lpi.usra.edu/vexag). For the sake of brevity, these questions are not presented here in detail.

Summary

As we begin to discover terrestrial exoplanets orbiting other stars in our galaxy, some of them will be Venus-like, and learning how they reach this evolutionary state will be absolutely crucial for our understanding of the origin and longevity of habitable conditions on Earthlike planets. Pioneer Venus informed us about the past presence of water on Venus (Hunten, 1992). Its subsequent loss tells us that the history of water on Venus is even more significant for improving our capability to understand future Earth climates as the rising surface temperatures lead to increasing water vapor in the atmosphere which in turn raises the saturation vapor pressure, the same process that is believed to have raised the surface temperature on Venus and led to the loss of its (surface) water (Sagan, 1960).

A common thread for Venus and Mars is that the atmospheres on both planets appear to have undergone catastrophic change--Mars may have lost almost all its atmosphere, while Venus may have driven off much of the water in a runaway greenhouse and perhaps increased its atmosphere. While atmospheric studies of Mars and Venus are thus linked by this common thread of dramatic change, understanding Venus' current and past climate is more germane to understanding our own. It is therefore prudent that exploration of Venus receive at least a fraction of the resources that have been devoted to Mars.

“What happened to the water” is the question that has been a major driver of NASA’s efforts to explore Mars in the last two decades with Mars Observer, Mars Pathfinder, Mars Polar Lander, Mars Climate Orbiter, Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter, Phoenix, and Spirit and Opportunity Rovers. NASA is now poised to launch the Mars Science Laboratory in November 2011. ESA is also participating in the exploration of Mars with its Mars Express and through a joint effort with NASA for future missions, and an international Mission to Mars led by Russia (Phobos Grunt) is also poised for launch in November 2005. In contrast to this very healthy and scientifically productive set of missions to Mars, the Magellan radar surface mapper, launched in 1989, is the last dedicated NASA mission to our other planetary neighbor, Venus, where “what happened to the atmosphere” is a paramount question also. ESA’s Venus Express, the flight spare version of Mars Express, is a small step towards obtaining needed observations.

Efforts focusing on the evolution of Venus will help us understand not only the evolution of Earth but terrestrial planets around other stars as well. Since exoplanets are being discovered ever more rapidly, it is even more important to understand Venus and its evolution in order to interpret the more detailed data that will be obtained on exoplanets in the near future. This is in addition to the urgency in understanding planetary atmospheres well enough to save our own. Venus marks the inner boundary of the habitable zone in our solar system. As most of humanity would agree, it should be at least as important to learn about the Earth's future as its past.

In summary, Venus exploration now is crucial to:

1. better understand the role of the greenhouse effect on heating planetary atmospheres
2. better understand how the global super rotating hurricane-force winds can arise and get organized into a tropical cyclone-like vortex and be sustained in Earth-like atmospheres
3. better understand how the planets in the inner solar system, including Earth, formed and evolved
4. better understand plate tectonics on Earth, and
5. better understand the future of the Earth's environment, especially its climate

To conclude, we need to study Venus to better understand Earth's future now.

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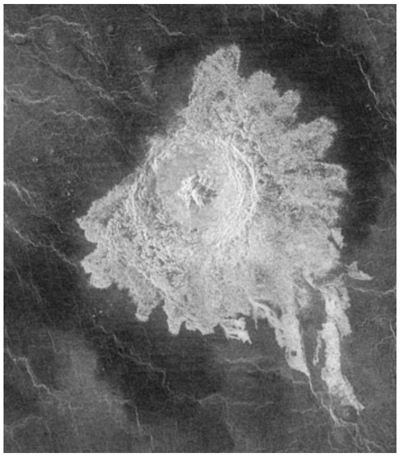


Venus impact crater Aurelia, about 20 miles across, is surrounded by a thick blanket of ejected material. A small "tail" of melted rock flowed away from the crater to the lower right.

APPENDIX B. CURRENT AND FUTURE VENUS MISSIONS

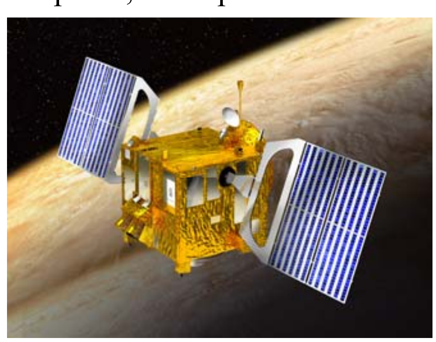
ESA's Venus Express orbiter mission continues to be the only dedicated mission to study Venus at present. The mission has been extended through December 2014 pending a successful review by ESA in 2012. The spacecraft continues to function well and the project is exploring aerobraking operations and new science from a shorter orbit beyond 2014. Future observations of Venus will be provided by the Japanese Akatsuki and the proposed Russian Venera-D missions.

Europe's Venus Express Mission

Venus Express is the first Venus exploration mission of the European Space Agency and built using space Mars Express spacecraft and instruments. Launched in November 2005, it arrived at Venus in April 2006 and has been continuously sending back science data from its polar orbit around Venus. Equipped with seven science instruments, the main objective of the mission is the long-term observation of the Venusian atmosphere. The observation over such long periods of time has never been done in previous missions to Venus, and is key to better understanding of the atmospheric dynamics. It is hoped that such studies can contribute to an understanding of atmospheric dynamics in general, while also contributing to an understanding of climate change on Earth. Venus Express operations are approved by ESA through 31 December 2014, subject to validation in 2012. Venus Express experiments are:

- **ASPERA** (Analyzer of Space Plasmas and Energetic Atoms) investigates the interaction between the solar wind and the Venusian atmosphere.
- **VMC** (Venus Monitoring Camera) is a wide-angle, multi-channel charge-coupled device (CCD) designed for global imaging of the planet.
- **MAG** (Magnetometer) measures the strength and direction of the Venusian magnetic field as affected by the solar wind and Venus itself.
- **SPICAV** (SPectroscopy for Investigation of Characteristics of the Atmosphere of Venus) is an imaging spectrometer that analyzes IR and UV radiation of stars and the Sun as they are occulted by the Venusian atmosphere. SOIR (Solar Occultation at Infrared) is an additional IR channel used to observe the Sun through the Venusian atmosphere.
- **VIRTIS** (Visible and Infrared Thermal Imaging Spectrometer) is a near-UV, visible, and IR imaging spectrometer for remote sensing of the atmosphere, surface, and surface/atmosphere interaction phenomena.
- **Radio Science**: VeRa (Venus Radio Science) is a radio sounding experiment that provides data for analysis of the ionosphere, atmosphere and surface of Venus.

Venus Express data are available at ESA's Planetary Science Archive and NASA's PDS Atmospheres Node. Additional information about Venus Express can be found at: http://www.esa.int/SPECIALS/Venus_Express/index.html



Artist's concept of Venus Express spacecraft operating at Venus since 2006. Courtesy of ESA.

Japan's Akatsuki Mission

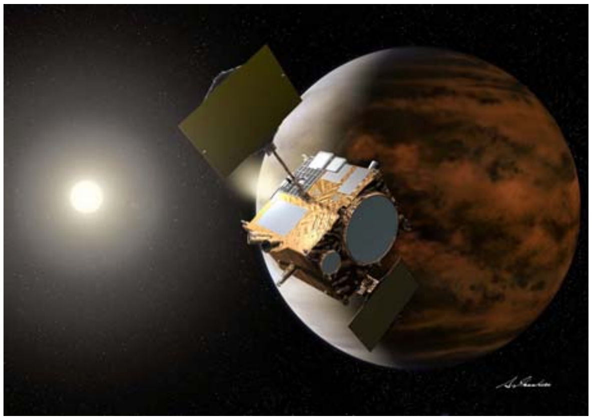
Akatsuki (aka PLANET-C and Venus Climate Orbiter) is a Japanese mission to study the atmosphere of Venus. Akatsuki was designed to enter an elliptical orbit, with pericenter and apocenter of 300 to 80,000 km respectively, and an orbital period of 30 hours. This enables a partial synchronization with the super-rotation of the Venusian atmosphere. Thus, Akatsuki will observe the same cloud patterns for consecutive orbits. Akatsuki has carrying a suite of instruments for remote sensing in IR, visible, and UV.

Akatsuki was launched on 21 May 2010 on the H-IIA rocket from Tanegashima Space Center. During a 6.5-month cruise from Earth to Venus, Akatsuki achieved the following: (1) took images of the Earth with 3 on-board cameras (UVI, IR1, and LIR); (2) acquired star-field images including the ecliptic-plane scan (for zodiacal light measurement) with IR2; and (3) imaged the Earth and the Moon with 4 cameras (UVI, IR1, IR2, and LIR) from the distance of about 30 million km. Akatsuki's orbit insertion on December 7, 2010 failed; and it is now in orbit around the Sun with an orbital period of about 200 days. At this orbital period—which is just 10% shorter than that of Venus—Akatsuki will encounter Venus again in 2016–2018, after 11 revolutions around the Sun.

Akatsuki's instruments are:

- **IR1 and IR2**: IR cameras operating a 1- and 2-µm wavelengths to observe the surface, clouds, cloud particles sizes, and H_2O vapor
- **UVI**: Ultraviolet Imager to observe cloud-top SO_2 and the "unknown Absorber"
- **LIR**: Long Wavelength IR Camera to observe cloud top temperatures
- **LAC**: Lightening and Airglow Camera to observe lightening and oxygen airglow
- **RS**: Radio Science X-Band Ultrastable Oscillator for radio occultation observations of the neutral and ionized atmospheres of Venus

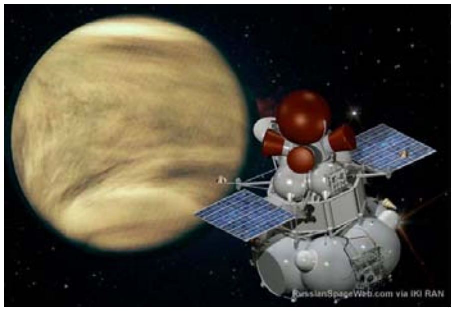
Additional information about Akatsuki can be found at: http://www.stp.isas.jaxa.jp/venus/top_english.html and http://www.isas.jaxa.jp/e/enterp/missions/planet-c/index.shtml



Artist's concept of Japanese Venus Climate Orbiter at Venus (Courtesy of JAXA)

Russia's Venera-D Mission

The Venera-D (Венера-Д) probe is a proposed Russian Venus space probe, being considered for launch beyond 2016. Venera-D's prime purpose is to make a host of remote-sensing observations of Venus and is also intended to map future landing sites. Venera-D will serve as the flagship for a new generation of Russian-built Venus probes, culminating with a lander capable of withstanding the harsh Venusian environment for more than the 1½ hours logged by the previous Russian probes. In order to keep research and development costs down, the new Venera-D probe will resemble the previous Russian probes, but will rely on new technologies developed by Russia since its last Venus missions (Vega 1 and Vega 2 in 1985). Venera-D will most likely be launched on the Proton booster, but may be designed to be launched instead on the more powerful Angara rocket. Venera-D will follow the Phobos-Grunt mission, the first Russian Mars mission since the 1990s.



Artist's concept of the Venera-D spacecraft

Venera-D will consist of an orbiter, two atmospheric balloons, microprobes, and the lander. The orbiter would be used to relay data back to Earth from scientific payloads in the atmosphere and on the surface of Venus. In addition, the orbiter's science goals would be investigate the composition of the Venusian atmosphere and its circulation patterns. Two balloons operating for 8 days at 55–60 km and 45–50 km would be dropped from the lander during its descent and would measure acoustic and electrical activities in the Venus atmosphere. Also, up to four microprobes would be dropped from balloons; they would continuously probe the atmosphere in multiple locations during their 30-minute descent. A lander, based on the Venera design, is also planned, capable of surviving for a long duration on the planet's surface. This lander would study the atmosphere and clouds during its descent and analyze soil after its touchdown. Instruments would be:

- Orbiter
  - Fourier Imaging UV Spectrometer
  - High-Resolution Limb Spectrometer
  - Wide-Angle CCD Camera
  - Radiometer
  - Fields and Particles Sensor
- Balloons
  - Meteorological Instrument Suite
  - Mini-Fourier Spectrometer
  - Nephelometer
  - CCD Camera
  - Radiometer
- Lander
  - Neutral Mass Spectrometer
  - Surface Properties Instrument Suite
  - Meteorological Instrument Suite
  - Mini-Fourier Spectrometer
  - CCD Camera
  - Seismometer
  - Nephelometer
  - Radiometer

APPENDIX C. VENUS LABORATORY MEASUREMENTS AND GODDARD SPACE FLIGHT CENTERTEST CHAMBER

Laboratory Measurements of Venus System Variables and Processes

In addition to the missions for future Venus exploration described in the previous section, new laboratory measurements are needed to maximize the science return from current and future Venus missions. These measurements, shown in Table B-1, can be divided into two categories: Category 1 are laboratory data necessary for retrieving Venusian system variables from calibrated instrument data, and Category 2 are laboratory data necessary for characterizing fundamental Venusian processes based on newly revealed Venusian system variables.

There are four basic physical regimes for the new laboratory measurements: (1) the atmosphere above the clouds, in which the temperature and pressure conditions are similar to those in the terrestrial atmosphere; (2) the sulfuric-acid-laced cloud layer; (3) the atmosphere below the clouds, in which the temperature and pressure range is unique for solar system exploration; and (4) the super-heated surface. Many of these laboratory measurements could be conducted in a Venus Environmental Test Facility, which would simulate pressure, temperature, and atmospheric composition as a function of altitude. This would provide insights into how elements behave in the Venusian environment and would also enable development and testing of new instruments and subsystems to operate under relevant conditions.

Table B-1. New Laboratory Studies to Support Future Venus Exploration

Context	Category 1 Measurements of Venus System Variables	Category 2 Measurements of Venus System Processes
Atmosphere above the clouds	Trace constituent atmospheric sounding: mm/sub-mm spectral line pressure-broadening coefficients	Excited atom/molecule-molecule reaction rates, for example, O* + CO_2
	Molecular spectral parameters: frequency, transition strengths (cross sections) in IR, submillimeter, etc.	Reaction rate parameters for sulfur- and chlorine-containing species in a CO_2 – dominated atmosphere
Cloud layer	Cloud composition: optical properties of sulfuric acid aerosols under the conditions experienced in the clouds of Venus, especially at the lower temperatures of the upper clouds	Aerosol formation and properties
	Cloud composition: effects of various likely impurities (i.e., sulfur allotropes and other photochemical byproducts) on the scattering and absorbing properties of these aerosols	Cloud microphysics: critical saturation for nucleation under Venus cloud conditions
		Cloud microphysics: charging properties of the cloud aerosols could be investigated in a manner similar to terrestrial aerosol charging
Atmosphere below the clouds	Atmospheric IR opacity: Very high-pressure, high-temperature CO_2 and H_2O spectroscopy, isotopologues, O_3, O_2, H_2, etc.	Molecular spectral parameters: frequency, transition strength (cross sections), line shape, pressure-induced absorption, particularly CO_2 and its isotopologues

Context	Category 1 Measurements of Venus System Variables	Category 2 Measurements of Venus System Processes
	Near-surface atmospheric sounding: cm wavelength properties of CO_2 and OCS >30 bars	
	Supercritical CO_2 in new temperature range at high pressures	
Surface	Chemical weathering of surface materials (basalts): reaction rates, decomposition rates	Scattering properties
	Spectroscopic (visible, near-IR) characteristics of various ferric/ferrous, silicate, sulfate, and hydroxide under Venus conditions	
	Surface conductivity sounding: dielectric loss properties at 750 K for various basalts and other major rock types	
	Atmospheric IR opacity: Very high-pressure, high-temperature CO_2 and H_2O spectroscopy, isotopologues, O_3, O_2, H_2, etc.	
	Fundamental thermophysical data: specific heat, speed of sound, equation of state, thermal expansion coefficients	
Technical issues	Stability of spacecraft materials, and rates of reaction/corrosion with hot supercritical CO_2-SO_2 gas	
	Chemical transfer of elements from surface into atmosphere (and onto spacecraft windows?)	

A Venus Environmental Test Facility would enable:

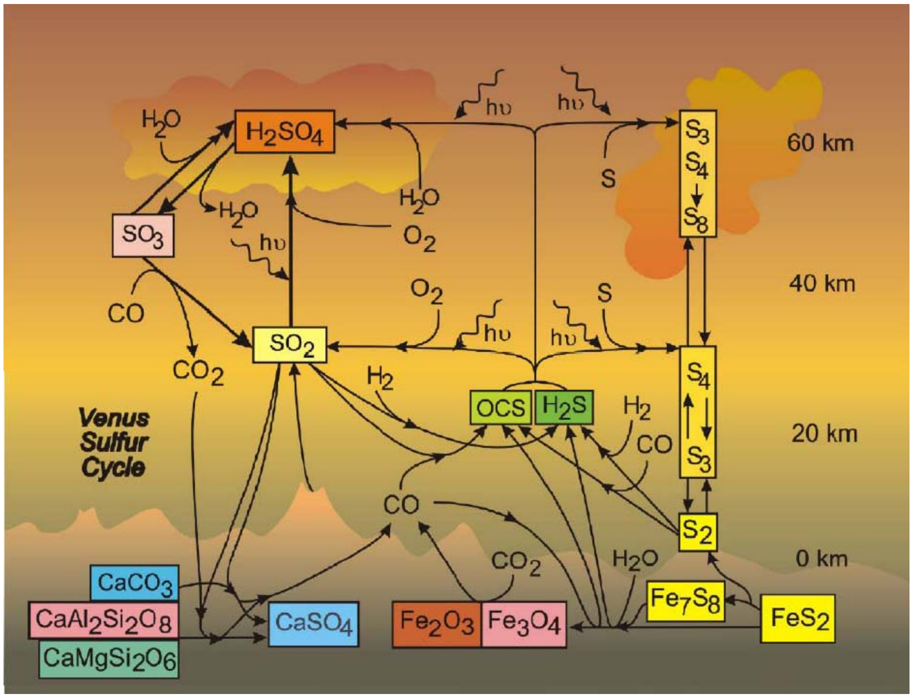
- Understanding the chemistry in the atmosphere above the cloud tops: There is a shortage of laboratory measurements under Venusian atmospheric conditions that would enable accurate determinations of the atmospheric properties. In addition, for understanding what acquired measurements reveal about atmospheric processes, there is a shortage of laboratory measurements for key parameters of relevant reaction processes, particularly those unique to a sulfur-rich atmosphere.
- Understanding the physical and chemical properties of the sulfurous cloud layers: There is a shortage of laboratory measurements at Venusian cloud conditions related to the optical properties of different candidate cloud aerosols. Thus, new laboratory measurements concerning aerosol formation and properties are required to understand the formation of these clouds.
- Understanding the significance of the composition in the atmosphere below the clouds: A region of high temperature and pressure, new laboratory measurements on the optical properties of different molecular constituents, including sulfur compounds, are required.

- Understand the rates of reaction of surface weathering processes: New laboratory studies under Venusian surface conditions are required to ascertain rates of chemical weathering of potential surface minerals, spectroscopic parameters for possible Venusian surface materials, measurements of conductivity of surface materials, and fundamental thermophysical data. Laboratory investigations and studies of analog environments on Earth will provide the necessary information to support future Venus measurements and their interpretation.

Facilities for laboratory investigations at extreme Venusian temperature and pressure conditions can be small and devoted to particular investigations. Larger chambers for spacecraft and instrument testing under Venusian conditions would enable the general scientific community to perform laboratory investigations. Chambers that can maintain stable pressures and temperatures for longer durations are needed to study reaction rates.

Venus Test Chamber at Goddard Space Flight Center

A Venus environmental test facility is being demonstrated via a small pressure chamber at Goddard Space Flight Center. The chamber is available to the community for testing of small flight components/ instruments and relatively short duration experiments that require high temperatures and pressures. Time for using the pressure chamber can be applied for through the ROSES announcement of opportunity (e.g., Planetary Instrument Definition and Development Program, or PIDDP) or inquiries can be made directly to the manager of the Venus Test Chamber, Natasha Johnson (natasha.m.johnson@nasa.gov). A fact sheet for this and other environmental test chambers is given below.

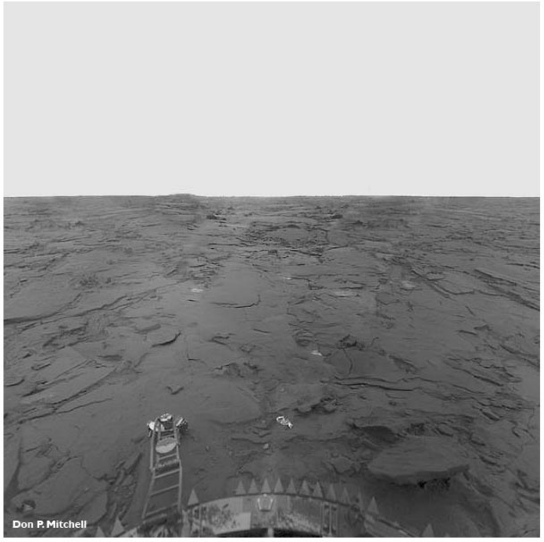


Artist's concept of the chemical reactions taking place in the Venusian atmosphere

VENUS ENVIRONMENTAL TEST FACILITY CAPABILITY LIST

Provided by Rodger Dyson and Natasha Johnson

Location	Volume (ft^3)	Dimensions (ft by ft)	Pressure (bar)	Temperature (°C)	Species	Notes	Public/ROSES Availability
NASA JPL	0.0009	.049 by .49	1 to 1000	20 to 1000	CO_2, N_2, SO_2	Accelerated Weathering	Yes
MIT	0.001	0.04 by 1	1 to 200	20 to 700	CO_2	Pressure or temperature	No
LANL	0.005	0.04 by 1	1 to 10,000	20 to 150	CO_2	LIBS/RAMAN	No
Univ. of Wisconsin	0.008	0.05 by 1	1 to 270	20 to 650	CO_2	DOE Reactor Corrosion	No
MIT	0.02	0.08 by 4	1 to 200	20 to 700	CO_2	Pressure or temperature	No
NASA GSFC	0.13	0.41 by 1	1 to 95.6	20 to 500	CO_2, N_2, SO_2	Materials	Yes
NASA JPL	0.45	0.33 by 5.25	1 to103	20 to 500	CO_2, N_2,H_20, SO_2, CO, He, Ne, Ar	RLVT, Optical Access	Yes
NASA JPL	0.5	.59 by 1.83	1 to 103	20 to 500	CO_2, N_2,H_20, SO_2, CO, He, Ne, Ar	VMTF, Materials and Small Systems	Yes
Georgia Inst of Technology	1.05	1.16 by 1	1 to 100	20 to 343	CO_2, N_2	Higher altitude only	No
NASA Glenn	5.30	1.5 by 3	1 to 100	20 to 500	CO_2, N_2, SO_2	Any altitude, Under Construction	Yes (Fall 2012)
NASA Glenn	28.3	3 by 4	10^{-3} to 103	20 to 537	CO_2, N_2, SO_2, Ar, H_2O, CO, He, Ne, OCS, HCl, HF	Any altitude, Optical Access, Under Construction	Yes (Fall 2012)



The Venus surface observed by the Russian Venera lander showing a platey basaltic surface.

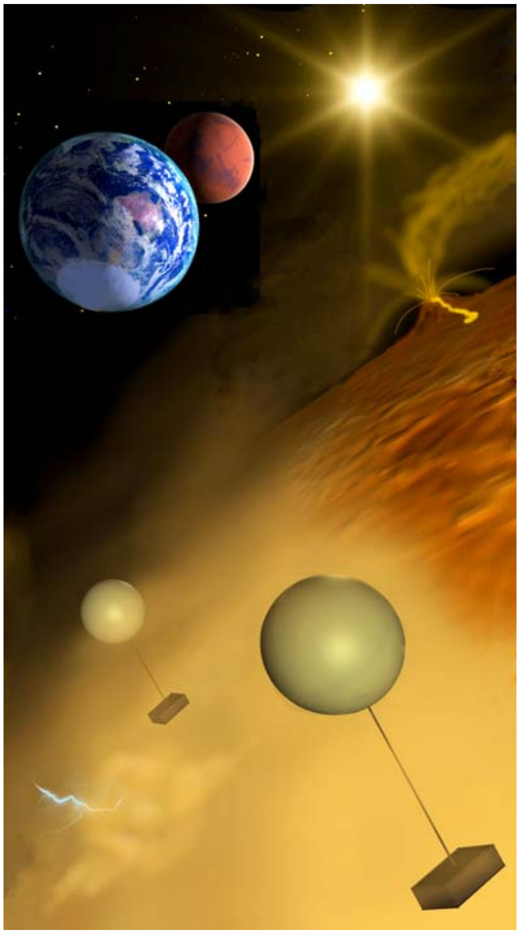
APPENDIX D. VENUS MISSION FACT SHEETS

Decadal Survey Venus Climate Mission

Decadal Survey Venus Intrepid Tessera Lander

Decadal Survey Venus Mobile Explorer

Venus Flagship Design Reference Mission



Artist's concept of balloon explorers flying in the Venusian skies. Such mobile vehicles, riding the strong winds of Venus under Earth-like temperature and pressure conditions, can explore the dynamics and active chemistry of Venus while also uncovering tell-tale clues to Venus' past locked in isotopic distributions of noble and light gases.

Venus Climate Mission

VCM

Planetary Science Decadal Survey

Mission Concept Study

VCM Science Objectives

- Characterize the strong CO_2 greenhouse atmosphere of Venus, including variability.
- Characterize the dynamics and variability of Venus's superrotating atmosphere.
- Characterize surface/atmosphere chemical exchange in the lower atmosphere.
- Search for atmospheric evidence of climate change on Venus.
- Determine the origin of Venus's atmosphere and the sources and sinks driving evolution of the atmosphere.
- Understand implications of Venus's climate evolution for the long-term fate of Earth.

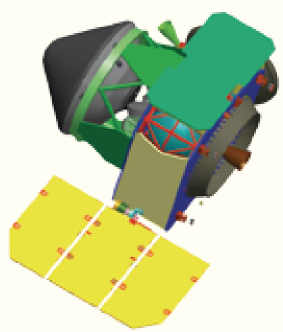
Mission Concept Study Report to the NRC Decadal Survey Inner Planets Panel

June, 2010

Concept Maturity Level: 4
Cost Range: Low End Flagship
Launch Date: November 2, 2021
Science Campaign:
April 7, 2022 - April 28, 2022
Launch Mass: 3,948 kg
Launch Vehicle: Atlas V 551

VCM Science Payload

- Carrier Spacecraft
  - Venus Monitoring Camera Vis-IR
- Gondola/Balloon System
  - Neutral Mass Spectrometer (NMS)
  - Tunable Laser Spectrometer (TLS)
  - Atmospheric Structure Instrumentation (ASI)
  - Nephelometer
  - Net Flux Radiometer (NFR)
- Mini-Probe
  - NMS; NFR; ASI
- Drop Sondes,
  - ASI; NFR

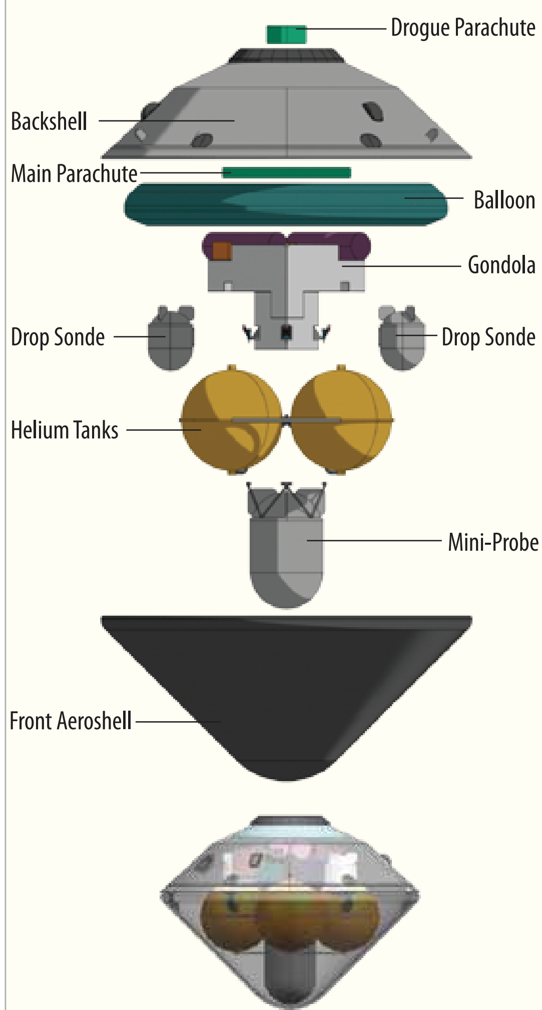


Carrier Spacecraft

Function: Deliver and deploy Entry Flight System; orbit Venus as communication relay for Gondola/Balloon system
Power: 5 m^2 solar panels
Attitude Control: 3-axis stabilized (Spin up for release of the EFS)
Telecom: 1.7m dia. HGA; two-way S-band comm. with gondola; two-way Ka-band comm. with Earth
Science Data Return: 14 Gb from Carrier Spacecraft Camera plus 142 Mb from Gondola/Balloon System; Mini-Probe and Drop Sondes

Entry Flight System

with Gondola/Balloon System, Mini-Probe and Drop Sondes



Mini-Probe
Function: 45 minute descent from 55.5 km to surface
Power: Distributed rechargeable Polymer Lithium-ion batteries
Telecom: 1 way S-band to gondola
Science Data Return: 5 Mb
Design: 44 cm dia., 66 cm tall titanium pressure vessel, passive thermal control

Drop Sondes (2)
Function: 45 minute descent from 55.5 km to surface
Power: Distributed rechargeable Polymer Lithium-ion batteries
Telecom: One-way S-band to gondola
Science Data Return: 1 Mb (each probe)
Design: 29 cm dia., 35 cm tall titanium pressure vessel, passive thermal control

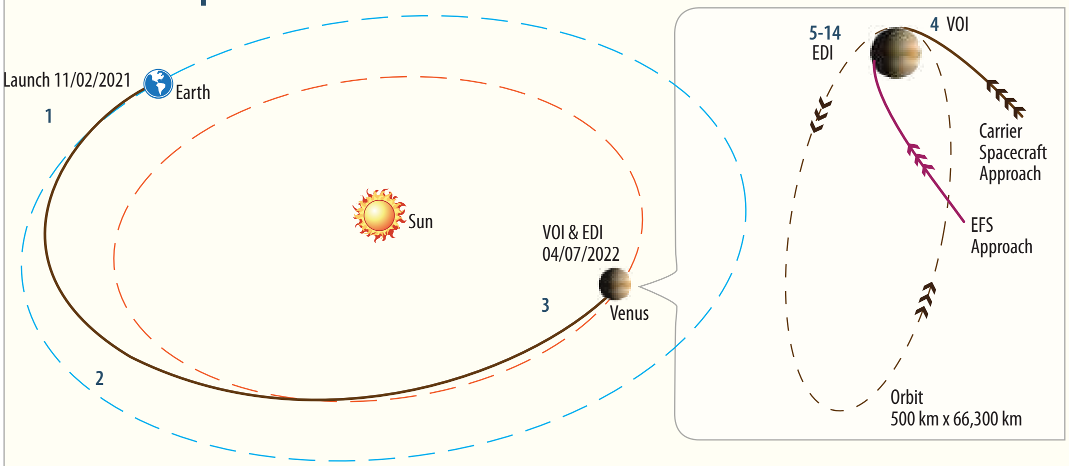
Entry Flight System
Function: Deliver in situ elements through the atmosphere; carries the Gondola/Balloon System, Inflation System, Mini-Probe and two Drop Sondes
Power: Lithium-thionyl chloride (Li-$SOCl_2$) primary battery
Design: Carbon-Phenolic front shell, Phenolic Impregnated Carbon Ablator back shell, 45 deg cone angle (Pioneer-Venus heritage), 2 m diameter

Gondola/Balloon System

Function: 21 day science campaign at 55.5 km float altitude
Power: Lithium-thionyl chloride (Li-$SOCl_2$) primary battery
Telecom: Two way S-band (plus Doppler) to Carrier Spacecraft; one way S-band from Mini-Probe and Drop Sondes
Science Data Return: 135 Mb from Gondola science + 7 Mb from Probe & Sondes science
Balloon Design: 8.1 m diameter helium filled balloon; teflon coated for sulfuric acid resistance; Vectran fabric plus Mylar film construction; metalized for low solar heating
Inflation System Design: 4 x 0.5 m dia. titanium tanks; pipes; valves

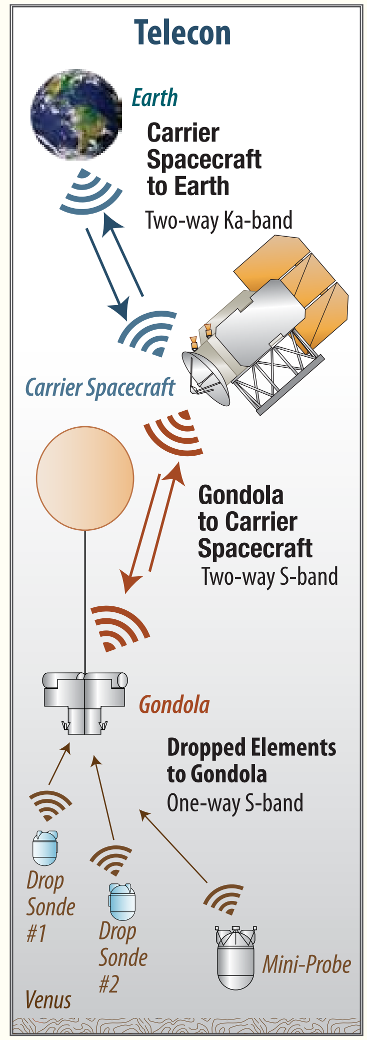
GSFC • JPL • ARC

VCM Mission Operations

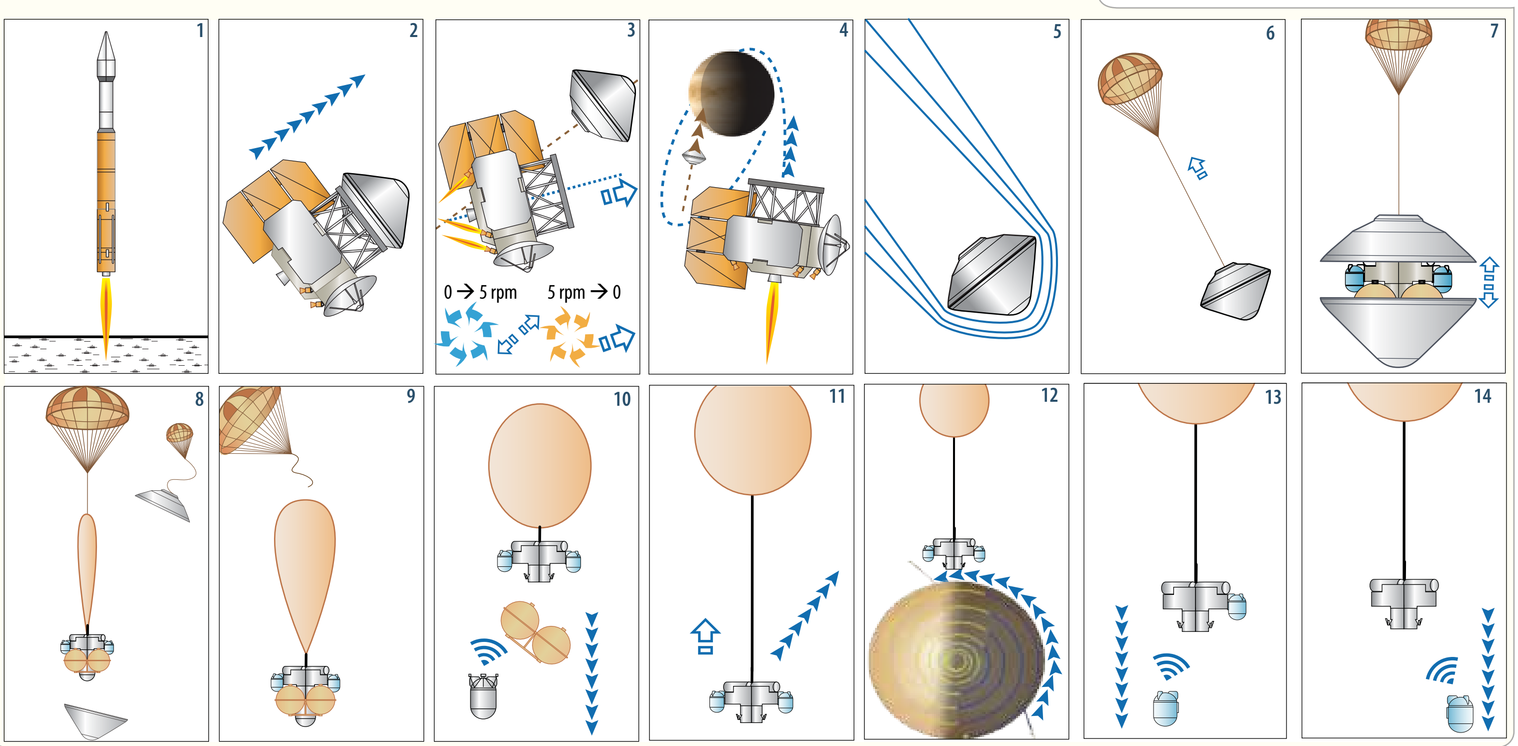


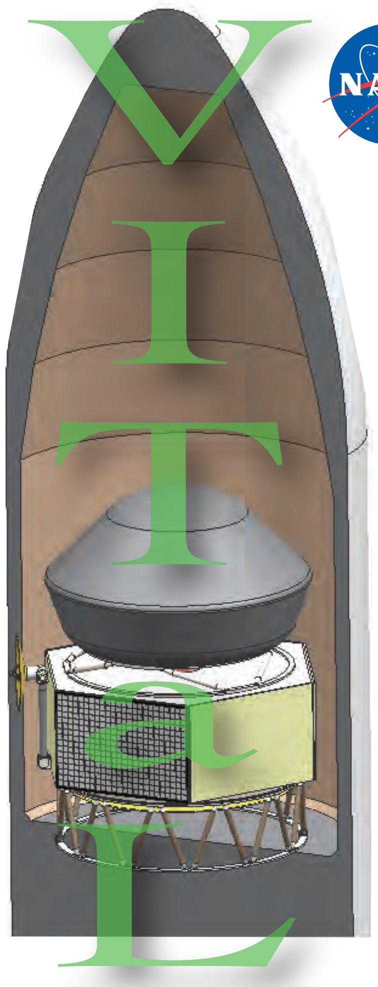
1. VCM launches in November 2021 on an Atlas V 551 L/V, with a C3 of 8.8 km^2/sec^2, capable of delivering up to 5,141 kg of mass
2. Five month cruise to Venus
3. Ten days prior to Venus entry, the Entry Flight System (EFS) is released with 5 rpm from the Carrier Spacecraft, a day later the Carrier Spacecraft diverts for a Venus Orbit Insertion (VOI) approach
4. Carrier Spacecraft performs VOI and enters an elliptic orbit to provide telecom support to the in situ elements (Gondola, Mini-Probe, two Drop Sondes)
5. EFS reaches atmospheric entry interface at 175 km altitude, decelerates over a minute
6. Drogue parachute opens at subsonic speeds, further decelerates the EFS
7. Aeroshell separates
8. Back and front Aeroshell jettison and Balloon inflation begins
9. Main parachute jettisons
10. Balloon inflation is completed in 5 minutes; Helium inflation tanks are jettisoned and the Mini-Probe is released at 53 km (lowest altitude)
11. Balloon chord extends as the Balloon rises to a float altitude of 55.5 km
12. Balloon begins its 21-day science operation, spiraling toward pole multiple times
13. First Drop Sonde is deployed on command or at a predetermined time
14. Second Drop Sonde is deployed on command or at a predetermined time

Telecon



Telecom strategies: The Probe and Sondes communicate data on S-band to the Gondola during their 45 min descent; the Gondola sends all science data to the Carrier Spacecraft; the Carrier Spacecraft relays all data (incl. Carrier Spacecraft camera) to Earth on Ka-band.

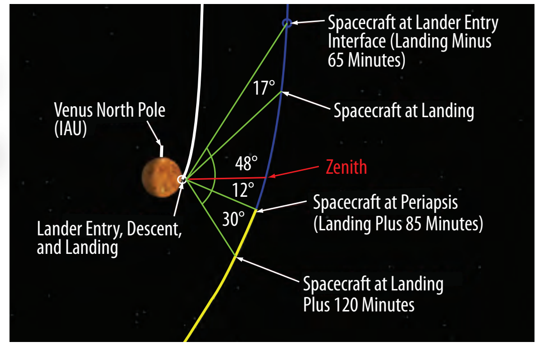




Venus Intrepid Tessera Lander

fact sheet

Mission Concept Study Report to the NRC Decadal Survey
Inner Planets Panel • March 15, 2010
Concept Maturity Level: 4 • Cost Range: Low End Flagship
GSFC • ARC



Note: At zenith the carrier S/C is directly overhead of the lander.

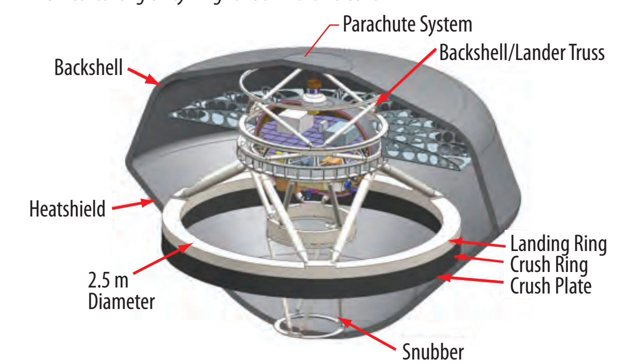
Nominal Mission:

- Atlas V 551 Launch Vehicle
- Type II trajectory
- Launch on 11/2/2021
- Venus fly-by 4/7/2022
- Descent/Landed science 7/29/2022

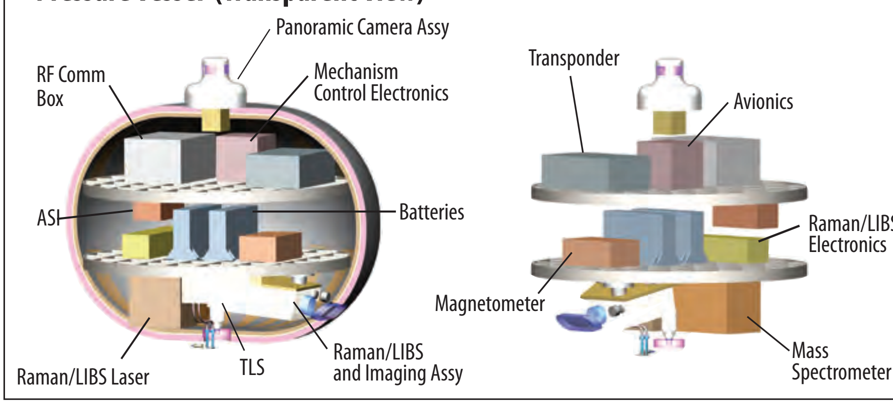
Mission Driving Science Objectives	Measurement	Instrument	Functional Requirement
Characterize chemistry and mineralogy of the surface.	Major, trace elements, mineralogy, NIR spectroscopy	Raman/LIBS; NIR (1.0 micron) descent imager below 1 km, Raman/LIBS context camera	Access to tessera terrain, > 25 *in situ* sample measurements, sample context images
Place constraints on the size and temporal extent of a possible ocean in Venus's past.	Measure D/H ratio in atmospheric water, mineralogy and major element chemistry of surface rocks.	NMS; TLS; Raman/LIBS	*In situ* sampling of the upper and lower (<16 km) atmosphere. Access to and measurement of tessera terrain.
Characterize the morphology and relative stratigraphy of surface units.	Visible and NIR observations of multiple surface units at cm to m scale spatial resolution.	NIR (1.0 micron) descent imager and surface panoramic camera with ~5 filters from 550-1000 nm.	Position of cameras to image the surface, while accommodating expected slopes, platform stability for clear images.

Lander Aeroshell (Cruise Configuration)

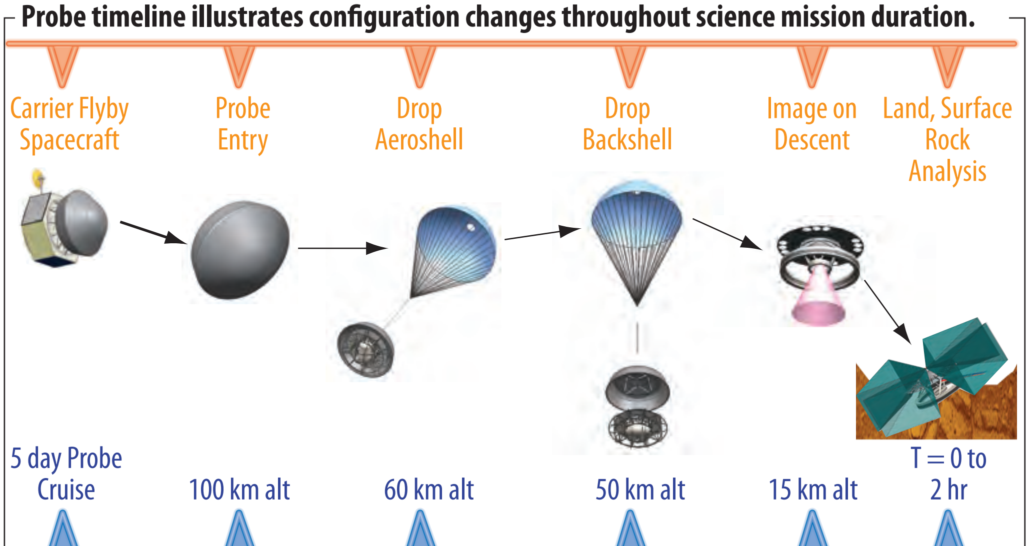
A low center of gravity Ring Lander in the Aeroshell



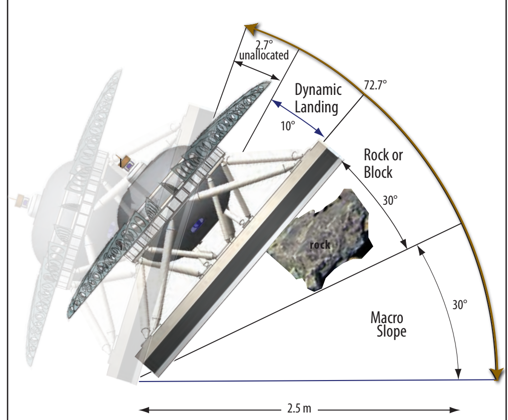
Pressure Vessel (Transparent View)



Probe timeline illustrates configuration changes throughout science mission duration.



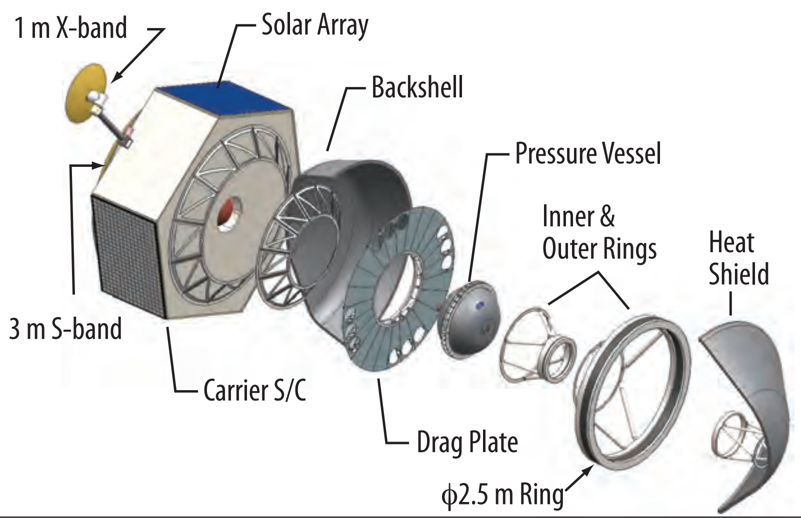
Ring design landing slope capability.



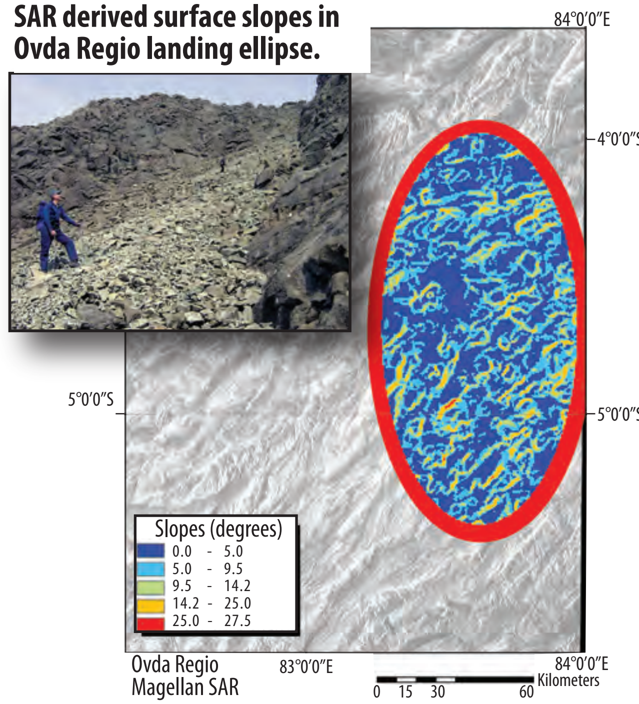
Venus Intrepid Tessera Lander

fact sheet

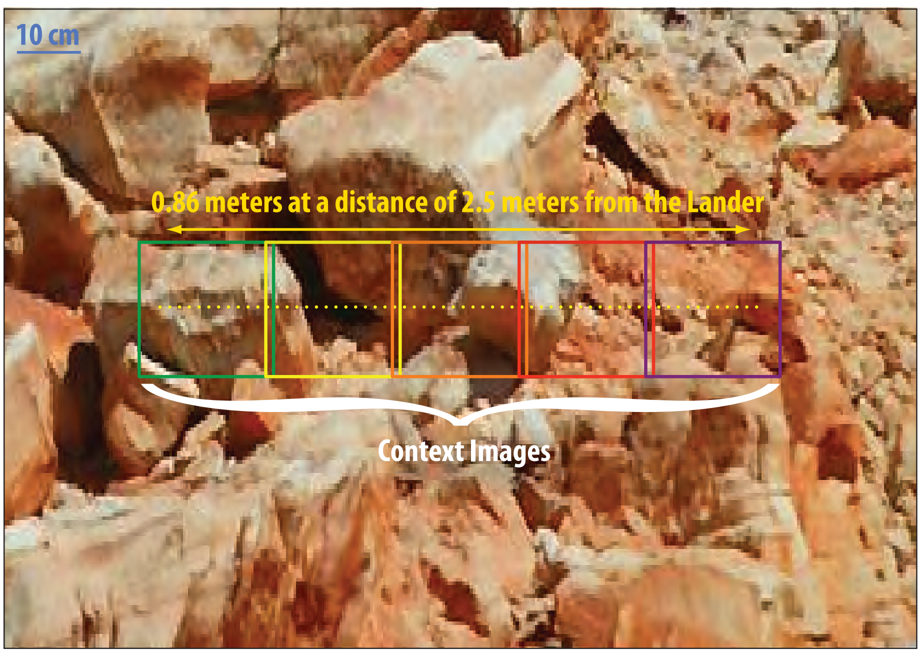
Exploded view of Carrier Spacecraft, Aeroshell, and Lander

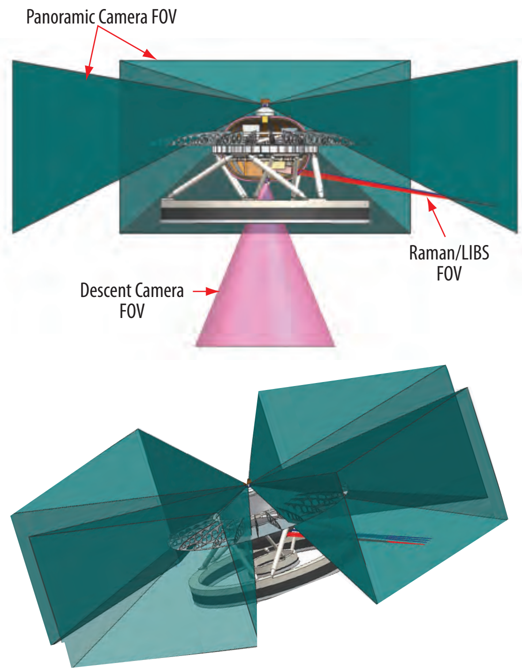


SAR derived surface slopes in Ovda Regio landing ellipse.

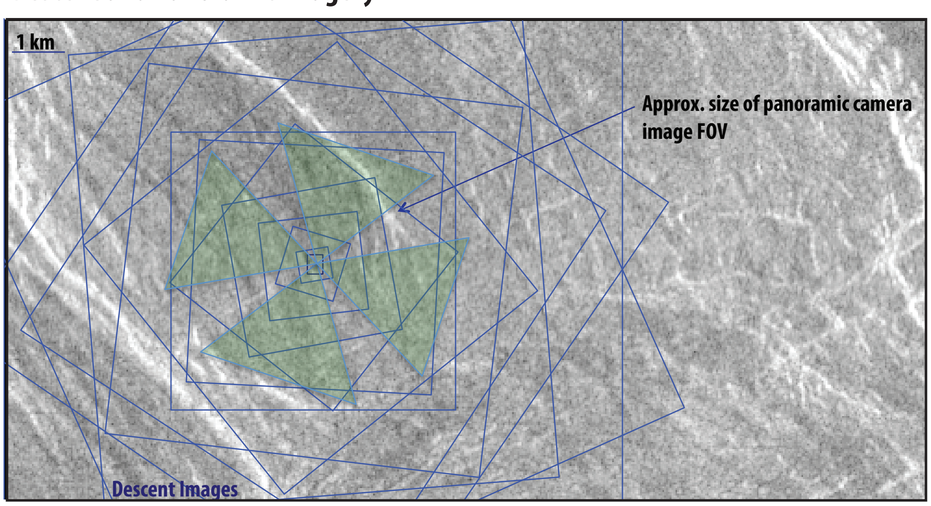


Raman/LIBS Survey Measurements and Context Images





Descent and Panoramic Imagery



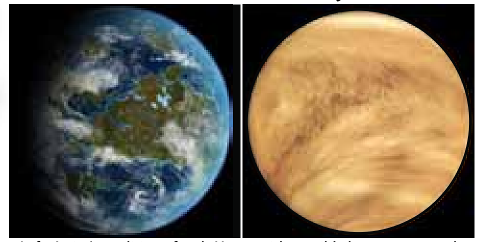
Mass Breakdown

Component	CBE [kg]	Allow [%]	Max Mass [kg]
Lander	1051	30%	1366
Lander Science Payload & Accum.	48	30%	63
Lander Subsystems	1002	30%	1303
Mechanical/Structure	283	30%	368
Landing System	603	30%	784
Thermal	67	30%	87
Power	12	30%	16
Avionics	28	30%	36
RF Comm	9	30%	12
Aeroshell	1051	30%	1379
Spacecraft	846	30%	1100
Satellite *(S/C + Probe)* Dry Mass	2948	30%	3845
Satellite Wet Mass	3299	30%	4200
LV Throw Mass available to lift Wet			5141

Venus Mobile Explorer

fact sheet

Mission Concept Study Report to the NRC Decadal Survey
Inner Planets Panel • December 18, 2009
Concept Maturity Level: 4 • Cost Range: Low End Flagship
GSFC • JPL • ARC



Left: Artist's rendition of early Venus with possible large oceans and a significant hydrologic cycle; Right: Venus today with a dry, thick CO_2 greenhouse atmosphere resulting in surface temperatures of 450°C and pressures in excess of 90 bar.

Nominal Mission:

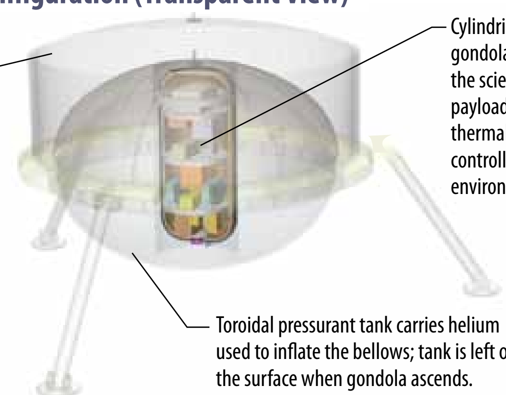
- Atlas V 551 Short Fairing Launch Vehicle
- Type II trajectory
- Launch on 5/27/2023
- Venus fly-by 10/27/2023
- Landed science 2/15/2024
  - atmospheric chemistry
  - surface chemistry in 2 locations
  - 8 - 16 km aerial imaging traverse

Mission Driving Science Objectives	Measurement	Instrument	Functional Requirement
Determine the origin and evolution of the Venus atmosphere, and rates of exchange of key chemical species between the surface and atmosphere	In situ measurements of Noble gas isotopes, trace gas mixing ratios and trace gas isotopic ratios	Neutral Mass Spectrometer (NMS) combined with Tunable Laser Spectrometer (TLS)	In situ sampling of the atmosphere as functions of altitude and time
Characterize fundamental geologic units in terms of major rock forming elements, minerals in which those elements are sited, and isotopes	Identify mineralogy and elemental chemistry of surface rocks in 2 locations separated by > 8 km	Laser Raman/Laser Induced Breakdown Spectrometer (LIBS)	Land in 2 locations, ~2 m path-length for compositional observation; stable platform for measurement duration
Characterize the geomorphology and relative stratigraphy of major surface units	Airborne near IR imaging along a transect ~8 km in length, at < 5 m spatial resolution	Near infrared (~1.1 micron) imager (FOV TBD, and SNR > 100)	Near-surface aerial mobility; >45° solar incidence, contiguous images of the surface during aerial traverse; 5 hour near surface operational lifetime

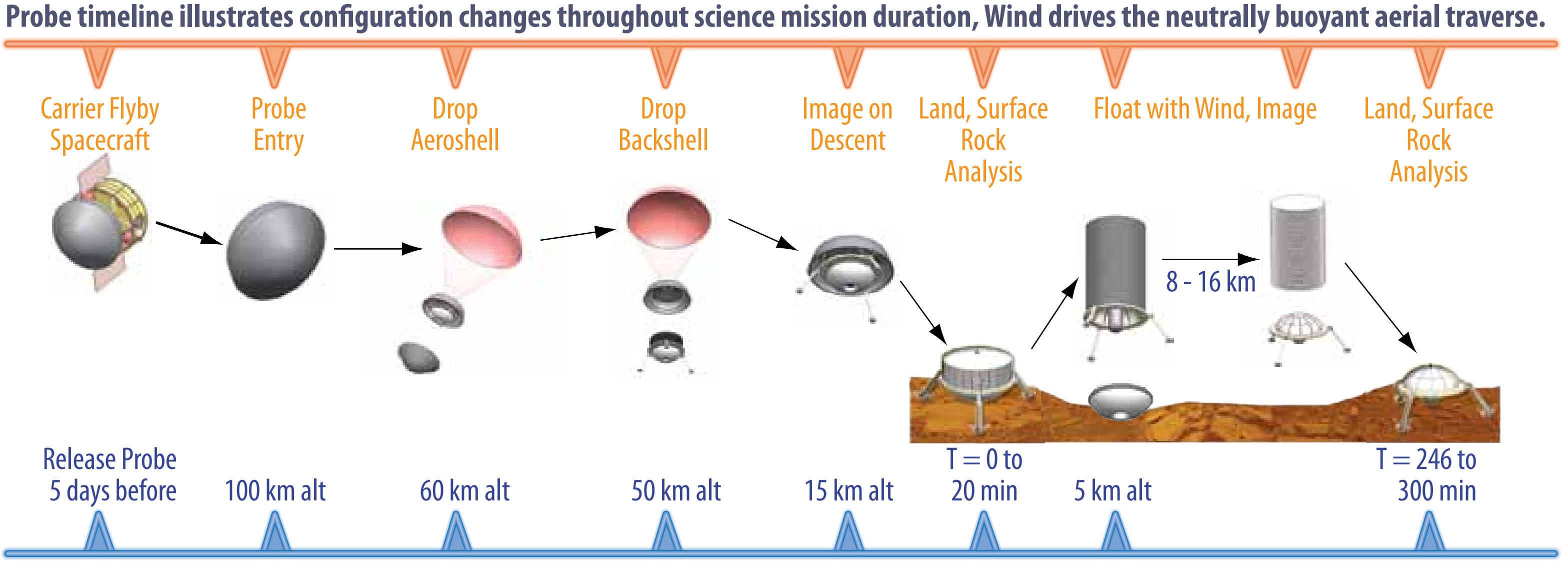
Lander Aeroshell (Cruise Configuration)

The innovative compact design of the science payload into a central cylinder surrounded by a toroidal pressurant tank and capped by the metallic bellows, allows the VME to be accommodated in an accepted aeroshell geometry.

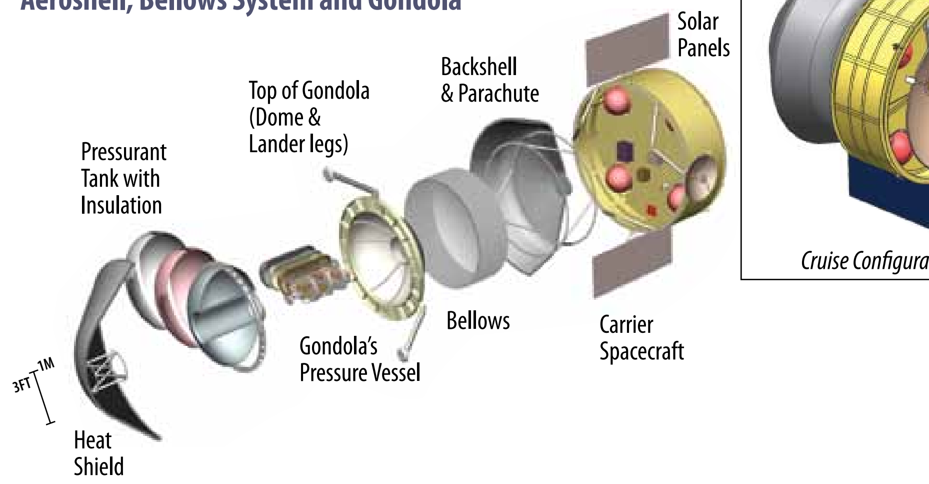
Gondola in Landed Configuration (Transparent View)



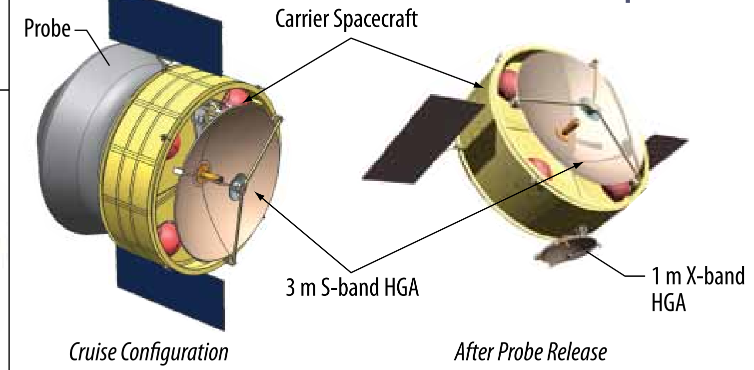
Probe timeline illustrates configuration changes throughout science mission duration, Wind drives the neutrally buoyant aerial traverse.



Exploded view of Carrier Spacecraft, Aeroshell, Bellows System and Gondola



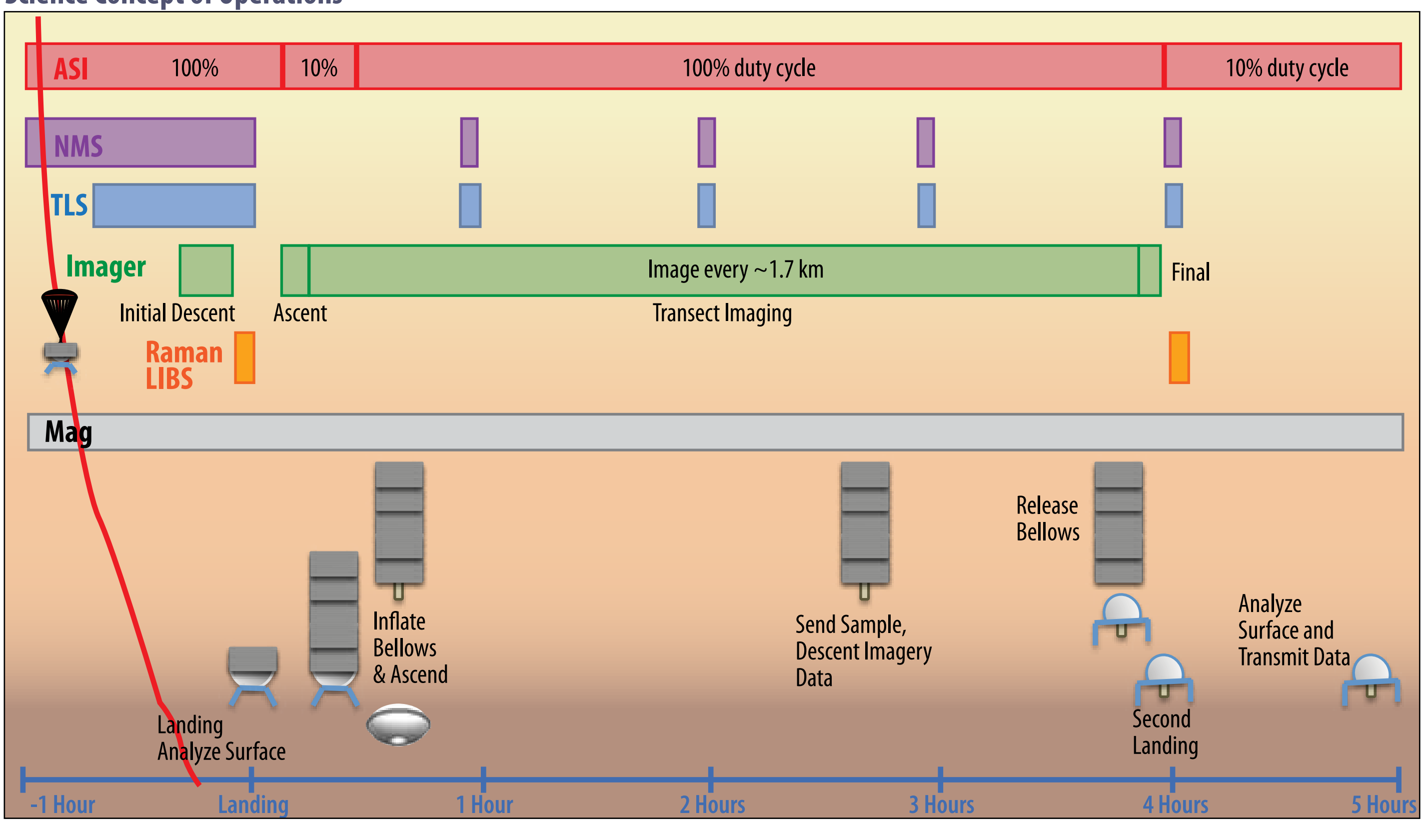
Carrier Spacecraft



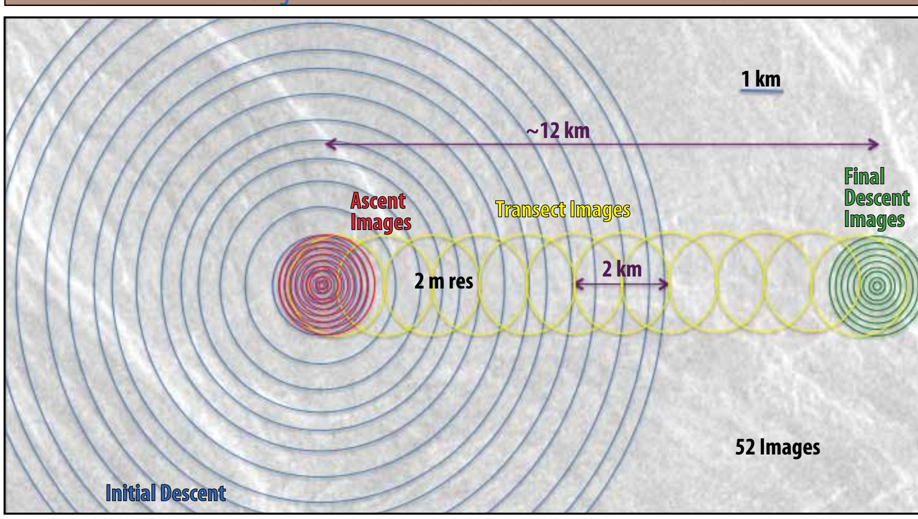
Carrier Telecom

Antenna	Wavelength	Purpose
3 m HGA mesh	S-band	Probe to Carrier uplink
2 omni-directional	X-band	Carrier to Earth contingency
1 m HGA solid	X-band	Carrier to Earth Science

Science Concept of Operations



ASI = Atmospheric Structure Investigation; Mag = Magnetometer



Nominal example of imaging sequence assuming ~12 km aerial traverse. IR Images are taken on initial descent from 15 km to the surface (blue), on ascent (red), as the gondola floats with the wind under the bellows (yellow) and on final descent (green), collecting 52 images.

Mass Breakdown

Component	CBE [kg]	Allow [%]	Max Mass [kg]
Lander	1390	30%	1782
Lander Science Payload	31	30%	41
Lander Subsystems	469	30%	609
Mechanical/Structure	270	30%	351
Mechanisms	51	30%	66
Thermal	113	30%	147
Other	34	30%	44
Bellows	890	30%	1132
Aeroshell	876	30%	1139
Spacecraft	846	30%	1100
Satellite *(S/C + Probe)* Dry Mass	3112	30%	4021

National Aeronautics and Space Administration

NASA's Flagship Mission to Venus

A Future Mission Concept

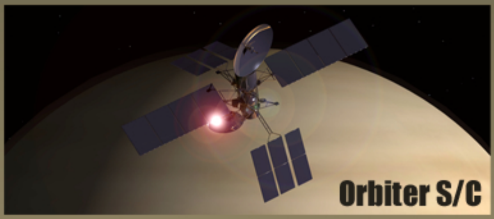
Venus Flagship Science Themes and Objectives

Science Theme	Science Objective
What does the Venus greenhouse tell us about climate change?	Understand radiation balance in the atmosphere and the cloud and chemical cycles that affect it
	Understand how superrotation and the general circulation work
	Look for evidence of climate change at the surface
How active is Venus?	Identify evidence of current geologic activity and understand the geologic history
	Understand how surface/atmosphere interactions affect rock chemistry and climate
	Place constraints on the structure and dynamics of the interior
When and where did the water go?	Determine how the early atmosphere evolved
	Identify chemical and isotopic signs of a past ocean
	Understand crustal composition differences and look for evidence of continent-like crust

Science Payload for the Design Reference Mission

Orbiter	2 Balloons	2 Landers	
Lifetime (4 years)	(1 month)	Descent Phase (1–1.5 hour)	Landed Phase (5 hours)
InSAR — Interferometric Synthetic Aperture Radar	ASI — Atmospheric Science Instrument (pressure, temperature, wind speed,)	ASI	Microscopic imager
Vis–NIR Imaging Spectrometer	GC/MS — Gas Chromatograph / Mass Spectrometer	Vis–NIR Cameras with spot spectrometry	XRD / XRF
Neutral Ion Mass Spectrometer	Nephelometer	GC / MS	Heat Flux Plate
Sub–mm Sounder	Vis-NIR camera	Magnetometer	Passive Gamma Ray Detector
Magnetometer	Magnetometer	Net Flux Radiometer	Sample acquisition, transfer, and preparation
Langmuir Probe	Radio tracking	Nephelometer	Drill to ~10 cm
Radio Subsystem (USO — Ultra Stable Oscillator)			Microwave corner reflector

Mission Elements



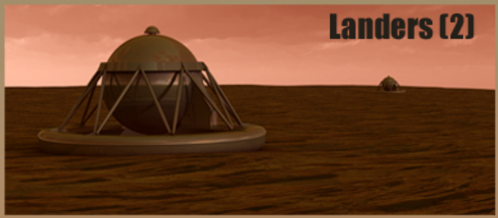
Orbiter S/C

Launch Vehicle
Atlas V-551 (w/ 5-m diameter fairing)
Mass (CBE + Cont.)
5306 kg (wet); 2275 kg (dry); Payload mass: 290.4 kg
Power
32 square meter solar panels (9868 W EOL)
Telecom
4-m Ka/X-band (Orbiter-to-Earth to 34-m DSN antennas); 0.5-m S-band (Orbiter-to-in situ); 2.5-m S-band (Orbiter-to-in situ)
Functions
Relay telecom support for in situ elements (30 days); 6 months of aerobraking to science orbit; Science orbiter (2 years baseline & 2 years extended)
Overall Mission Science Data Return
~300 Tbits of data to Earth over 2 years of science operations

Carrier S/C

Launch Vehicle
Atlas V-551 (5-m diameter fairing)
Mass (CBE + Cont.)
5578 kg (wet) w/ entry systems; 1640 kg (wet) w/o the carried two entry systems
Power
4.4 square meter solar panels
Attitude Control
3-axis stabilized; (Spin up for release of entry systems)
Telecom
2.5-m dual-feed X/S-band HGA (Carrier-to-Earth to 34-m DSN antennas; and Carrier-to-in situ); 2.5-m S-band fixed HGA (Carrier-to-in situ)
Functions
Delivery & deployment of entry systems; & backup relay telecom

Mass (CBE + Cont.)
686 kg; Payload mass: 106.2 kg
Lander Design
0.9-m diameter titanium shell (1-cm wall thickness); Rotating pressure vessel; Drill to 10-cm (2 samples)
Thermal Design
Passive thermal management: Lithium nitrate phase change material (PCM); Silica insulation: 5-cm external; 1-cm internal; Carbon dioxide backfilled pressure vessel
Power
Llithium-thionyl chloride primary batteries (the same cells used on the balloons), (6 kWh, 12.6 kg)
Telecom
S-band LGA to Orbiter with Electra (backup to flyby s/c)
Functions
Descent science for ~1 hour; Surface science for 5 hours



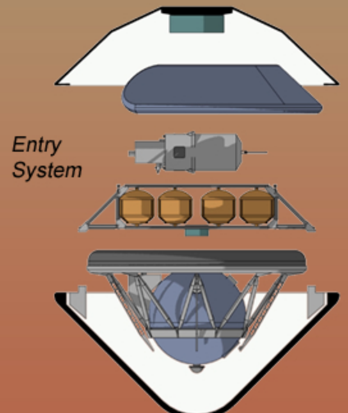
Landers (2)

Entry Systems (2)

Mass (CBE + Cont.)
1969 kg each entry system
Design
Thermal Protection System: Carbon-Phenolic
Aeroshell
45° half cone angle (Pioneer-Venus heritage); 2.65-m diameter; Spin stabilized after release from carrier
Functions
Entry systems deliver the in situ elements safely through the atmosphere; Each entry system carries a balloon & a lander with supporting subsystems

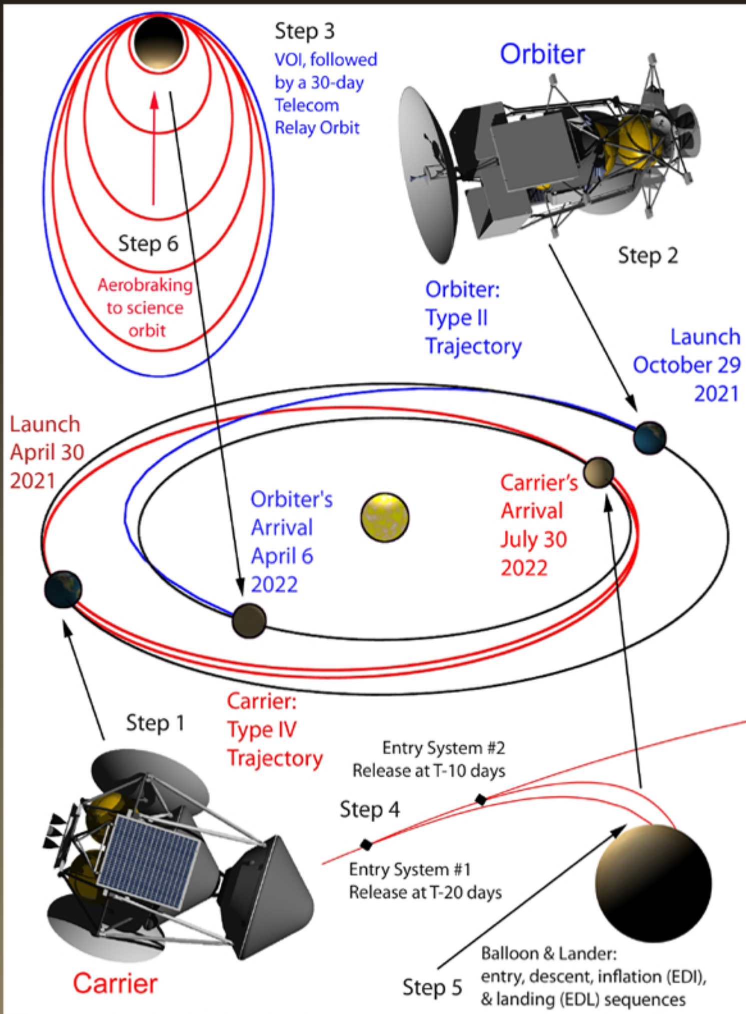
Balloons (2)

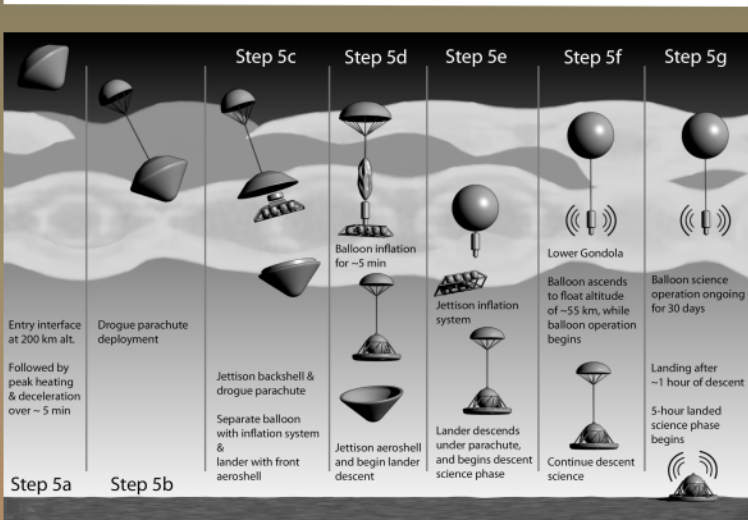
Mass (CBE + Cont.)
162.5 kg; Payload mass: 22.5 kg
Balloon design
7.1-m diameter helium filled superpressure balloon; Teflon coated for sulfuric acid resistance; Vectran fabric plus Mylar film construction; Metalized for low solar heating
Power
Lithium-thionyl chloride (Li-SOCl2) primary batteries (10.5 kWh, 22 kg)
Telecom
S-band to Orbiter (w/ backup to carrier flyby s/c); (plus carrier signal to Earth for Doppler and VLBI data)
Functions
30 days science operation at 55.5 km float altitude



Jet Propulsion Laboratory, California Institute of Technology

Mission Architecture Overview





- ***Step 1:*** Carrier spacecraft launch
  April 30, 2021 on an Atlas V-551 L/V (w/ 5-m diameter fairing)
  Type IV trajectory to Venus (arrives second after orbiter)
- ***Step 2:*** Orbiter spacecraft launch
  October 29, 2021 on an Atlas V-551 L/V (w/ 5-m diameter fairing)
  Type II trajectory to Venus (arrives first before carrier)
- ***Step 3:*** Orbiter arrives on April 6, 2022 (after 159-day cruise)
  Venus Orbit Insertion (VOI) maneuver
  300 km × 40000 km orbit for telecom relay support for (balloons & landers)
- ***Step 4:*** Carrier flyby on July 30, 2022 (after 436 days of cruise)
  Entry system #1 release: 20 days before carrier's Venus flyby
  Entry system #2 release: 10 days before carrier's Venus flyby
  Backup relay telecom support during lander's lifetime
- ***Step 5:*** Staggered entry for entry systems
  (13 hours phasing – one orbiter revolution)
  Entry, Descent, & Inflation (EDI) phases for the balloons
  Entry, Descent, & Landing (EDL) phases for the landers
  - ***Step 5a:*** Pre-entry phase: entry system (w/ balloon & lander) cruises to Venus
  - ***Step 5b:*** Atmospheric entry; entry heating; deceleration; Deployment of drogue parachute.
  - ***Step 5c:*** Separation of aeroshell into two parts; Main chutes open for balloon & lander elements Balloon released from backshell storage container.
  - ***Step 5d:*** Full balloon inflation in ~5 minutes
  - ***Step 5e:*** Helium inflation system jettisoned; Balloon rises to 55.5 km equilibrium altitude; Lander continues its descent to the surface; descent science
  - ***Step 5f:*** Balloon cord extended
    One-month balloon science mission phase begins
    Balloon data relayed to orbiter, then relayed to Earth
  - ***Step 5g:*** Lander reaches the ground after 1 hour of descent
    Begins 5-hour surface science operations phase
    Lander data relayed to orbiter, then relayed to Earth
- ***Step 6:*** Orbiter completes relay telecom support phase:
  6 months of aerobraking to 230 km circular orbit;
  2 years of orbiter science operations in prime mission
  (sufficient propellant for 2-year extended mission)

Mission Cost Estimate

- Mission cost: **$2.7B to $3.8B in $FY09**

Cost assumptions:

- Technology Readiness Level: TRL-6 by 2016.
- Schedule: 24 month duration for Phases A & B;
  52 month duration for Phases C & D.
- Mission class: the overall mission is Class A, as is the orbiter.
- Landers & balloons: single-string, redundancy through multiple mission elements.
- No contributed hardware from foreign partners.
- Pre-Phase A technology development funding at the level of 1-2% of the total mission cost.

Team Members

Venus STDT Members
Chair: Mark Bullock (SwRI)
Co-Chair: David Senske (JPL)

NASA & JPL
Jim Cutts (JPL)
Adriana Ocampo (NASA HQ)

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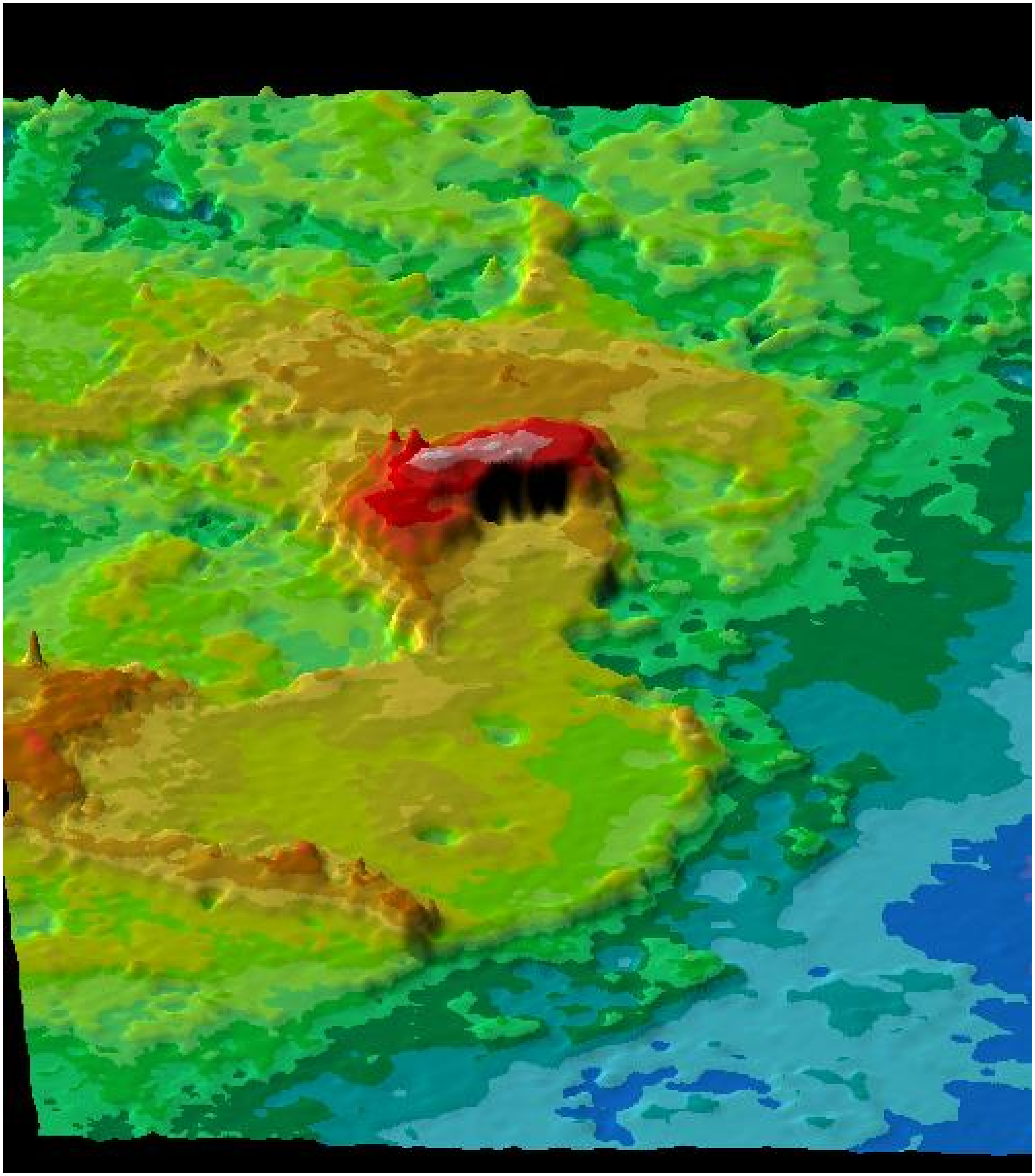
Team-X Design Team



Perspective view of Ishtar Terra, one of two main highland regions on Venus.The smaller of the two, Ishtar Terra, is located near the north pole and risesover 11 km above the mean surface level. Courtesy NASA/JPL–Caltech.