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

VEXAG MEETING 9–AUGUST 2011

This 2011 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.

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)
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FOREWORD

This version of VEXAG’s *Venus Exploration Goals and Objectives* is being 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 5 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 findings and proposed actions, which have been updated to reflect current circumstances. 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 is an overview of current and future Venus missions. Appendix B describes new laboratory measurements needed to maximize the science return from current and future Venus missions. Appendix C 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 document.

1.1. Why Venus Now?

Venus proximity to Earth and its similarity in size and bulk density to Earth’s have earned it the title of “Earth’s twin”. The lack of seasons and oceans to help transport heat and momentum suggest that the Venus atmosphere would be relatively simple. Yet we understand very little about this very alien world next door. Indeed, the contrast between the extreme 450°C Venus surface temperature, sulfuric acid clouds, and its divergent geologic evolution have challenged our fundamental understanding of how terrestrial planets, including Earth, work. The absence of plate tectonics on Venus helped move models away from an emphasis on buoyancy to an understanding of the function of lithospheric strength, convective vigor, and the role of volatile history in controlling these processes. Venus is the planet where the importance of the greenhouse effect was first realized, and where winds blow with hurricane force nearly everywhere across the planet, from the first km above the ground to above 100 km altitude and from the equator to the high polar region. What powers such global gales when the planet itself rotates at a speed slower than the average person can walk on Earth is unknown?

The study of the links between surface, interior, and climatic processes on Venus supports the idea that Venus could represent the fate of the Earth. The realization that two such similar planets could produce this extreme range of processes and conditions makes Venus an essential target for further exploration as we move out in the universe and discover Earth-like planets beyond our solar system. Recent results from Mars show that liquid ground water was limited to the first billion years of its evolution, during its geologically active period. Europe’s Venus Express has provided new reasons to explore Venus now. Surface thermal emissivity observations suggest tantalizing evidence of more evolved crustal plateaus, suggesting possible past oceans. Observations of surface emissivity variations from Venus Express suggest the presence of geologically recent flows. This recent volcanism has important implications for both interior dynamics and present day climate. As climate evolution comes into sharp focus on Earth, we must resume exploration of the planet that serves as an extreme end member.

1.2. Overarching Theme for Venus Exploration

With the context provided by the Venus White Papers prepared for the Planetary Science Decadal Survey, VEXAG adopted an overarching theme for Venus exploration: Venus and Implications for the Formation of Habitable Worlds. This theme is supported by three equally important goals with their prioritized objectives and investigations (Table 1-1).
• **Origin and Evolution**: How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and conditions of habitable environments on Venus and similar extrasolar systems?

• **Venus as a Terrestrial Planet**: What are the processes that have shaped and still shape the planet?

• **Climate Change and the Future of Earth**: What does Venus tell us about the fate of Earth’s environment?

### 1.3. Venus Exploration Goals

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

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

The surface of Venus appears to have been shaped, for the most part, within the geologically recent past, likely within the past 500 million to one billion years. The Venus surface, however, may contain evidence of the planet’s earlier history and origin (which may be accessible through a more complete characterization of the surface than previously accomplished), as well as a deeper understanding of the nature and evolution of the interior dynamics. In addition, detailed-chemical measurements of the composition of the atmosphere (in particular, the noble gases and their isotopes) provide additional information about the origin and evolution of Venus. Of particular interest is the possibility that Venus, early in its history, had long-lived oceans and a climate amenable to the development and evolution of life—possibilities that are not excluded by current knowledge. In summary, the objectives of Goal 1 are to:

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

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

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

Venus geologic processes are also largely dissimilar from those on Earth, aside from volcanic eruptions. The surface of Venus appears to have been resurfaced within the past 500 million to one billion years, obscuring possible signatures of earlier geological episodes. The nature and duration of this resurfacing remain enigmatic. Subsequent to resurfacing, styles of tectonism and volcanism evolved as the planet cooled, such that the thermal/dynamic regime of the planet is now thought to be a convection under a stagnant or sluggish lid. There are no manifestations of the global-plate tectonic processes like those on Earth. Analyses of gravity and topography data suggest that Venus has a comparable number of active large mantle plumes as Earth, as well many hundreds of smaller scale plumes that may also be active. Although there is little information on current levels of volcanic or tectonic activity, some atmospheric data suggest that Venus is still volcanically active. Exploring and characterizing processes on and in Venus are needed to understand dynamical, chemical, and geologic processes on other planets throughout our galaxy. The objectives of Goal 2 are to:

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

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

Although the terrestrial planets formed at about the same time within the inner solar system, from similar chemical and isotopic reservoirs, they have followed very different evolutionary paths. In particular, Venus and Earth, which formed at similar distances from the Sun with nearly identical masses and densities, now have vastly different atmospheres, surface environments, and tectonic styles. It has been suggested that Venus may have been more Earth-like earlier in its history and then evolved to its current state, and that Earth may ultimately transform to a hot, dry, inhospitable planet like Venus. It has become clear that, as on Earth, the climate balance of Venus reflects a dynamic balance between geologic and atmospheric processes. Thus, understanding the interior dynamics and atmospheric evolution of Venus provides insight into the ultimate fate of Earth. The objectives of Goal 3 are to:

1. Characterize the present-day greenhouse of Venus,
2. Determine if liquid water ever existed on the surface of Venus, and
3. Characterize how the Venus interior, atmosphere, and surface are interacting.
### Venus Exploration Goals and Objectives: August 2011

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

<table>
<thead>
<tr>
<th>Goal</th>
<th>Objective</th>
<th>Investigation</th>
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<tbody>
<tr>
<td><strong>Origin and Evolution</strong></td>
<td><strong>Understand atmospheric evolution</strong></td>
<td>Characterize elemental composition and isotopic ratios of noble gases in the Venus atmosphere, especially Xe, Kr, 40Ar, 38Ar, Ne, 4He, 3He, to constrain origin and sources and sinks driving evolution of the atmosphere. <strong>Determine isotopic ratios of H/D, 15N/14N, 17O/16O, 18O/16O, 34S/32S and 13C/12C in the atmosphere to constrain paleochemical disequilibria, atmospheric loss rates, the history of water, and paleobiosignatures.</strong></td>
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<tr>
<td></td>
<td><strong>Seek evidence for past changes in interior dynamics</strong></td>
<td>Characterize the structure, dynamics, and history of the interior of Venus, including possible evolution from plate tectonics to stagnant-lid tectonics. <strong>Characterize the nature of surface deformation over the planet’s history, particularly evidence for significant horizontal surface movement.</strong></td>
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<tr>
<td></td>
<td><strong>Determine if Venus was ever habitable</strong></td>
<td>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). <strong>Characterize gases trapped in rocks for evidence of past atmospheric conditions.</strong></td>
</tr>
<tr>
<td><strong>Venus as a Terrestrial Planet</strong></td>
<td><strong>Understand what the chemistry and mineralogy of the crust tell us about processes that shaped the surface of Venus over time</strong></td>
<td>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, &amp; isotopes. <strong>Characterize the chemical compositions of materials near the Venus surface as a function of depth (beyond weathering rind) to search for evidence of paleochemical disequilibria and characterize features of surface rocks that may indicate past climate or biogenic processes.</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Assess the current structure and dynamics of the interior</strong></td>
<td>Characterize the current structure and evolutionary history of the core. <strong>Place constraints on the mechanisms and rates of recent resurfacing and volatile release from the interior.</strong></td>
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## Venus Exploration Goals and Objectives: August 2011

### Venus as a Terrestrial Planet

<table>
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<tr>
<th>Characterize the current rates and styles of volcanism and tectonism, and how have they varied over time</th>
<th>Characterize active-volcanic processes such as ground deformation, flow emplacement, or thermal signatures to constrain sources and sinks of gases affecting atmospheric evolution.</th>
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<tr>
<td></td>
<td>Characterize active-tectonic processes through seismic, ground motion, or detailed image analysis.</td>
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<td>Characterize the materials emitted from volcanoes, including lava and gases, in terms of chemical compositions, chemical species, and mass flux over time.</td>
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<td></td>
<td>Characterize stratigraphy of surface units through detailed topography and images.</td>
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<td></td>
<td>Assess geomorphological, geochemical, and geophysical evidence of evolution in volcanic styles.</td>
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### Characterize current processes in the atmosphere

<table>
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<tr>
<th>Characterize the sulfur cycle through measurements of abundances within the Venus clouds of relevant gaseous and liquid/solid aerosol components such as SO₂, H₂O, OCS, CO, and sulfuric acid aerosols (H₂SO₄).</th>
<th>Determine the mechanisms behind atmospheric loss to space, the current rate, and its variability with solar activity.</th>
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<tr>
<td></td>
<td>Characterize local vertical winds and turbulence associated with convection and cloud-formation processes in the middle cloud region, at multiple locations.</td>
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<td></td>
<td>Characterize superrotation through measurements of global-horizontal winds over several Venus days at multiple-vertical levels (day and night) from surface to thermosphere.</td>
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<td></td>
<td>Investigate the chemical mechanisms for stability of the atmosphere against photochemical destruction of CO₂.</td>
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<td></td>
<td>Characterize local and planetary-scale waves, especially gravity waves generated by underlying topography.</td>
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<td></td>
<td>Measure the frequencies and strengths of lightning and determine role of lightning in generating chemically-active species (e.g., ÑΟₓ).</td>
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<td>Search for and characterize biogenic elements, especially in the clouds.</td>
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### The Future of Earth

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<tr>
<th>Characterize the Venus Greenhouse</th>
<th>Determine radiative balance as a function of altitude, latitude, and longitude.</th>
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<td>Measure deposition of solar energy in the atmosphere globally.</td>
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<td>Determine the size, distribution, shapes, composition, and UV, visible, and IR spectra, of aerosols through vertical profiles at several locations.</td>
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<td>Determine vertical-atmospheric temperature profiles and characterize variability.</td>
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### Climate Change and the Future of Earth

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<tr>
<th>Determine if there was ever liquid water on the surface of Venus</th>
<th>Determine isotopic ratios of H/D, 15N/14N, 17O/16O, 18O/16O, 34S/32S 13C/12C in solid samples to place constraints on past habitable environments (including oceans).</th>
</tr>
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<td></td>
<td>Identify and characterize any areas that reflect formation in a geological or climatological environment significantly different from present day.</td>
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<tr>
<td>Characterize how the interior, surface, and atmosphere interact</td>
<td>Determine abundances and height profiles of reactive atmospheric species (OCS, H₂S, SO₂, SO₃, H₂SO₄, Sn, HCl, HF, SO₃, ClO₂ and Cl₂), greenhouse gases, H₂O, and other condensibles, in order to characterize sources of chemical disequilibrium in the atmosphere.</td>
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<tr>
<td></td>
<td>Determine rates of gas exchange between the interior, surface and atmosphere.</td>
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2. VEXAG Findings and Proposed Actions

The first set of VEXAG findings and proposed actions was developed at the January 2007 VEXAG meeting and remained unchanged until the February 2009 meeting. NASA has acted on some of the proposed actions, particularly the formation of a Venus STDT in January 2007. The National Academies Planetary Science Decadal Survey Report was published in March 2011; it recommended the Venus Climate Mission (VCM) as a large class mission to be completed during the 2013–2022 decade following other higher priority but more expensive missions (Mars Sample Return (MAX-C), Jupiter Europa Orbiter (JEO), and Uranus orbiter (UO) as well as Enceladus Orbiter (EO). In June 2011 NASA announced the selection of three Discovery mission candidates for Concept Study Reports; the selection did not include a mission to Venus. This was followed by the New Frontiers-3 selection resulting in Venus In Situ Explorer (VISE) as a returning candidate mission in NF-4.

The current set of VEXAG findings and proposed actions, updated from that in the last version of this document [Pathways for Venus Exploration, September 2009], is presented here.

Decadal Survey Recommendation for VCM as Large Class Mission

Finding 1: VEXAG endorses the Planetary Science Decadal Study recommendation of a Venus Climate Mission (VCM) concept at the lower cost end of the Flagship class (mini-Flagship mission). Venus as an exploration target has a wealth of diverse yet interrelated regions to investigate: the thermosphere, the neutral atmosphere, the surface and interior. All of these regions are crucial to understanding the evolutionary history of Venus. This in turn would enable a better understanding of the climate evolution of terrestrial planets. The history of water on Venus is just as significant as it is on Mars. Its comparative study on the two planets is essential to gain a better insight into the past, present, and future of Earth. The Venus atmosphere, surface, and internal processes are coupled to volcanic processes responsible for the sulfur that produces Venus’s thick clouds and atmospheric chemistry—and perhaps the global circulation of super-rotating winds that still cannot be faithfully reproduced in numerical models today. The long-term interaction of the Venus surface and atmosphere is significant but poorly understood. With multiple, interrelated exploration goals, a revolutionary understanding of Venus can come through a mini-Flagship mission comprising an array of well-chosen instruments and platforms to obtain fundamental information both in-situ and from orbit.

Proposed Action 1: NASA should initiate an international study group to define the science goals, platforms, and experiments for an affordable mini-Flagship mission that can be undertaken in the coming decade and that effectively addresses the goals of the Planetary Science Decadal Study. VCM should be augmented as the budget allows the science community to address additional important Venus exploration goals. It is anticipated that effectively coordinated international participation can accomplish VCM goals at a substantially lower cost to NASA.

Venus Missions

Finding 2: There are multiple goals for exploring Venus—examining the thermosphere, the neutral atmosphere, and the surface and interior. All are crucial for the
understanding of the evolutionary history. Earth and Venus had a similar initial state, yet Earth is now habitable and covered in oceans while Venus has developed an intense greenhouse and lost its oceans. A full examination of the Venus thermal and volatile evolution is essential to understanding how terrestrial planets evolve. With multiple exploration goals, better understanding of Venus can come through multiple, narrowly focused missions. Coordinated implementation of these missions in most instances will lead to greater science return.

Proposed Action 2: NASA should follow the Planetary Science Decadal Survey themes by pursuing a balanced Venus exploration program that maximizes science return through coordinated mission implementation. For example, Venus missions support the “Building New Worlds” theme by providing data on accretion, water supply, chemistry, and internal differentiation as well as evolution of atmosphere and the effect of bombardment by large projectiles. In addition, Venus missions support the “Planetary Habitats” theme by providing data on how Venus had an ancient aqueous environment conducive to early life.

International Cooperation

Finding 3: In the current and near future period of constrained budgets, the flagship Venus Climate mission is more likely to be realized in the current decade with international partnerships. There is considerable interest in Europe, Japan, and Russia in missions to Venus as evidenced by two mission proposals to the Cosmic Vision M-3 opportunity, Japan’s on-going Akatsuki Mission, at present waiting for a second attempt at orbit insertion around Venus in late 2015, and Russia’s proposed Venera D mission.

Proposed Action 3: NASA should foster dialog with the international agencies and scientists and consider forming an International Venus Working Group to explore partnerships to implement the Decadal Survey recommended Venus Climate Mission.

Venus Community Support

Finding 4: The diminishing population and the lack of influx of young scientists into the Venus scientific community are concern. While Venus Express, the current ESA mission has helped, the absence of a NASA mission to Venus since Magellan has not enabled young scientists to explore and tackle Venus questions. The outcome of this unrealized research has created a gap and a delay in contributions to a better understanding of terrestrial climates.

Proposed Action 4: NASA should continue to support Participating Scientist Program (PSP) and consider expanding its scope or current and future international missions to Venus (e.g., ESA’s Venus Express mission). The PSP program for Akatsuki/Venus Climate Orbiter mission was discontinued following the failure of the spacecraft to achieve orbit in December 2011. At present, Akatsuki is in a solar orbit; JAXA will attempt to enter orbit around Venus in December 2015. Should this be successful, NASA should re-instate the Akatsuki/VCO PSP.
Technology

**Finding 5:** A plan for Venus technology development was created as part of the Venus Flagship Reference Design Mission. This plan is described in a Venus White Paper for the Planetary Science Decadal Survey—“Technologies for Future Venus Exploration” (Tibor Balint, James Cutts, Mark Bullock, et al.).

**Proposed Action 5:** NASA should support the technologies that enable the operation of medium to long-lived missions in the lower and upper (above 62 km) atmosphere and at the surface of Venus.

DSN S-Band Capability

**Finding 6:** DSN’s S-band uplink capability needs to be preserved to reliably communicate with Venus spacecraft missions in the Venus atmosphere and on the surface.

**Proposed Action 6:** Although the Planetary Science Decadal Survey endorsed preservation for only the S-band downlink capability at all NASA DSN facilities around the world, NASA should also preserve its S-band uplink capabilities at all of the DSN complexes.

*Magellan Radar Mosaic. Blues and greens are the lower plains areas; whites are the rugged highlands.*
3. Venus Exploration Mission Opportunities

To understand how the Venus goals and objectives 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 four missions of opportunity (instruments and investigations flown on a non-NASA spacecraft as well as extended missions for NASA spacecraft) have been selected. 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](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 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
Venus Exploration Goals and Objectives: August 2011

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 Venus’s 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 Venus’s atmosphere and between the surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles;
- Understand the physics and chemistry of Venus’s crust;
- Understand the properties of Venus’s atmosphere down to the surface and improve our understanding of Venus’s 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; and
- Search for planetary scale evidence of past hydrological cycles, oceans, and life and for constraints on the evolution of the atmosphere of Venus.

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
Earthlike 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 are
accomplished through in situ observations, coupled with simultaneous measurements in the
Venus atmosphere. The principal scientific objectives of VCM are 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 Venus atmosphere. In particular:

- Characterize the strong CO$_2$ greenhouse atmosphere of Venus.
- Characterize the dynamics and variability of the Venus 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 Venus atmosphere as well as the sources and sinks driving
evolution of atmosphere.
- Understand implications of the Venus 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 will enable the first truly global 3-dimensional
(and to a large extent 4-dimensional, via many measurements of temporal changes)
characterization of the Venus atmosphere. The mission will 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, Earthlike 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 extra-solar terrestrial planets. This mission does 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 conduct visible and IR monitoring of the Venus 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 will provide essential new constraints on the origin of crustal material and the history of water in Venus past. VITaL also provides 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 provide insight into the processes that have contributed to the evolution of the surface of Venus. The science objectives are 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 C. 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 Venus highlands (or volcanic regions) will provide essential new constraints on the origin of crustal material, the history of water in Venus past, and the variability of the surface composition within the unexplored Venus highlands. As the VME floats (~3 km above the surface) between the two surface locations, it offers new, high spatial resolution, views of the surface at near infrared (IR) wavelengths. These data provide insights into the processes that have contributed to the evolution of the Venus surface. The science objectives are 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 C.

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 C). 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 Venus atmospheric greenhouse work?
Venus Exploration Goals and Objectives: August 2011

- What does the surface say about Venus’ geological history?
- How does the Venus 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 Venus atmosphere?
- What atmospheric loss mechanisms are currently at work?
- What kind of basalts make up Venus’ 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 Venus Greenhouse Tell Us About Climate Change?** Addressed by characterizing the dynamics, chemical cycles, and radiative balance of the Venus atmosphere and by placing constraints on the evolution of the Venus 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 delivers the two landers and the two balloons to Venus on a Type-IV trajectory. The second launch vehicle delivers the orbiter on a Type-II trajectory to Venus. The orbiter arrives at Venus first, with sufficient time for checkout and orbit phasing before the landers and balloons arrive 3.5 months later. The orbiter supports two functions. First, it acts 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 transitions from its telecom relay phase to an orbital science phase with a 2-year remote sensing mission. The landers are designed for a 1-hour atmospheric descent followed by 5 hours of operation on the surface. The balloons and their payloads are 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 C 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


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

**Other references of interest are:**


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 plane, to be published by the International Space Science Institute, Bern, Switzerland, to be published in 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


“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


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


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

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 will be 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, University of Wisconsin, Madison, Wisconsin (sanjayl@ssec.wisc.edu) and Suzanne Smrekar, Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California (Suzanne.E.Smrekar@jpl.nasa.gov)

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November 2007 until Spring 2009
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VEXAG Web Master

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

VEXAG Focus Groups

Future focus groups may be formed to address specific VEXAG-identified study areas.

Artist conception of Venus lightning
6. Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASPERA</td>
<td>Venus Express fields and particles experiment</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
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<tr>
<td>DSN</td>
<td>Deep Space Network</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>IR1 and IR2</td>
<td>Akatsuki’s infrared cameras</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japanese Aerospace Exploration Agency</td>
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<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>JSpEC</td>
<td>JAXA Space Exploration Center</td>
</tr>
<tr>
<td>LAC</td>
<td>Akatsuki’s Lightening and Airglow Camera</td>
</tr>
<tr>
<td>LIR</td>
<td>Akatsuki’s long wavelength infrared camera</td>
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<tr>
<td>LPI</td>
<td>Lunar and Planetary Institute</td>
</tr>
<tr>
<td>MAG</td>
<td>Venus Express magnetometer experiment</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>PSP</td>
<td>Participating Scientist Program</td>
</tr>
<tr>
<td>R&amp;A</td>
<td>Research and Analysis</td>
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<tr>
<td>ROSES</td>
<td>Research Opportunities in Space and Earth Sciences</td>
</tr>
<tr>
<td>RS</td>
<td>Akatsuki’s Radio Science experiment</td>
</tr>
<tr>
<td>SPICAV–SOIR</td>
<td>Venus Express infrared and ultraviolet imaging spectrometer</td>
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<tr>
<td>STDT</td>
<td>Science and Technology Definition Team</td>
</tr>
<tr>
<td>UVI</td>
<td>Akatsuki’s ultraviolet imager</td>
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<tr>
<td>VCM</td>
<td>Venus Climate Mission</td>
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<tr>
<td>VCO</td>
<td>JAXA’s Venus Climate Orbiter (also known as Akatsuki and as Planet-C)</td>
</tr>
<tr>
<td>Vega</td>
<td>Russian Halley/Venus Lander and Orbiter Mission</td>
</tr>
<tr>
<td>VeRa</td>
<td>Venus Express radio science experiment</td>
</tr>
</tbody>
</table>
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 rises over 11 km above the mean surface level. Courtesy NASA/JPL–Caltech.
APPENDIX A. 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 Venus 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 Venus 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 Venus 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 Venus atmosphere. SOIR (Solar Occultation at Infrared) is an additional IR channel used to observe the Sun through the Venus 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 (Venus Climate Orbiter)

Akatsuki (PLANET-C) 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 Venus 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-micron wavelengths to observe the surface, clouds, cloud particles sizes, and H₂O vapor
- **UVI**: Ultraviolet Imager to observe cloud-top SO₂ 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 Venus neutral and ionized atmosphere

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 Venus 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.

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 Venus 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 B. VENUS LABORATORY MEASUREMENTS AND GODDARD SPACE FLIGHT CENTER TEST 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 Venus system variables from calibrated instrument data, and Category 2 are laboratory data necessary for characterizing fundamental Venus processes based on newly revealed Venus 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 Venus 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

<table>
<thead>
<tr>
<th>Context</th>
<th>Category 1 Measurements of Venus System Variables</th>
<th>Category 2 Measurements of Venus System Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere above the clouds</td>
<td>Trace constituent atmospheric sounding: mm/sub-mm spectral line pressure-broadening coefficients</td>
<td>Excited atom/molecule-molecule reaction rates, for example, O* + CO2</td>
</tr>
<tr>
<td></td>
<td>Molecular spectral parameters: frequency, transition strengths (cross sections) in IR, submm, etc.</td>
<td>Reaction rate parameters for sulfur- and chlorine-containing species in a CO2 – dominated atmosphere</td>
</tr>
<tr>
<td>Cloud layer</td>
<td>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</td>
<td>Aerosol formation and properties</td>
</tr>
<tr>
<td></td>
<td>Cloud composition: effects of various likely impurities (i.e., sulfur allotropes and other photochemical byproducts) on the scattering and absorbing properties of these aerosols</td>
<td>Cloud microphysics: critical saturation for nucleation under Venus cloud conditions</td>
</tr>
<tr>
<td></td>
<td>Cloud microphysics: charging properties of the cloud aerosols could be investigated in a manner similar to terrestrial aerosol charging</td>
<td></td>
</tr>
<tr>
<td>Atmosphere below the clouds</td>
<td>Atmospheric IR opacity: Very high-pressure, high-temperature CO2 and H2O spectroscopy, isotopologues, O1, O2, H2, etc.</td>
<td>Molecular spectral parameters: frequency, transition strength (cross sections), line shape, pressure-induced absorption, particularly CO2 and its isotopologues</td>
</tr>
</tbody>
</table>
### Venus Exploration Goals and Objectives: August 2011

<table>
<thead>
<tr>
<th>Context</th>
<th>Category 1 Measurements of Venus System Variables</th>
<th>Category 2 Measurements of Venus System Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-surface atmospheric sounding: cm wavelength properties of CO$_2$ and OCS &gt;30 bars</td>
<td>Scattering properties</td>
<td></td>
</tr>
<tr>
<td>Supercritical CO$_2$ in new temperature range at high pressures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>Chemical weathering of surface materials (basalts): reaction rates, decomposition rates</td>
<td></td>
</tr>
<tr>
<td>Spectroscopic (visible, near-IR) characteristics of various ferric/ferrous, silicate, sulfate, and hydroxide under Venus conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface conductivity sounding: dielectric loss properties at 750 K for various basalts and other major rock types</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric IR opacity: Very high-pressure, high-temperature CO$_2$ and H$_2$O spectroscopy, isotopologues, O$_3$, O$_2$, H$_2$, etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fundamental thermophysical data: specific heat, speed of sound, equation of state, thermal expansion coefficients</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical issues</td>
<td>Stability of spacecraft materials, and rates of reaction/corrosion with hot supercritical CO$_2$-SO$_2$ gas</td>
<td></td>
</tr>
<tr>
<td>Chemical transfer of elements from surface into atmosphere (and onto spacecraft windows?)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 Venus 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 Venus 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 Venus surface conditions are required to ascertain rates of chemical weathering of potential surface minerals, spectroscopic parameters for possible Venus 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 Venus temperature and pressure conditions can be small and devoted to particular investigations. Larger chambers for spacecraft and instrument testing under Venus 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 the test chamber is given below.
A bit of background...
As noted in a presentation to the scientific community by the VSTDT, “[The] key to enabling a Venus Flagship mission is the ability to conduct investigations and tests in Venus simulation chambers.” (LPSC 40). It was noted that “pressure and temperature mitigation technologies, whether high temperature electronics or efficient cooling mechanisms, must also be developed to a high level of readiness. Sensors and transducers that operate for long periods under ambient Venus conditions will also be required.”

The Essentials:
— Stainless Steel 316 Pressure Vessel
  ° Operates at max 95.6 bar (1,387 psi)
— Cylindrical Volume: Internal Dimensions (w/thermocouple well)
  ° Diameter: 12.7 cm (5 inches)
  ° Depth: 30.5 cm (12 inches)
— Computer monitored using NI LabView 2009, automated data logging

Operational Conditions:
— Pressure range (bars): 1 – 95.6
— Temperature range (K): 298 – 740
— Gases: pure CO₂ or N₂, or mixture (can include SO₂ at ppm levels)
— Maintains high P/T for a minimum of 48 hrs

Options:
— Feedthroughs for data/power/RF
  Configure as desired
— Sapphire viewports

Adjoining figures clockwise from top left:
Top of chamber – note optional inlets
Data throughput with 8 SS316 leads
Electrical side of chamber
Mechanical side of chamber

Questions, comments, availability?
Email: Natasha.M.Johnson@nasa.gov
Phone: 301-286-3919

Acknowledgements: The availability of this chamber would not be possible without the support of NASA and the Goddard Space Flight Center. Thanks are extended to Dr. William Byrd who originally built the chamber.
APPENDIX C. 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.
### 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

### 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

### Mini-Probe
- **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:** 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
1. VCM launches in November 2021 on an Atlas V 551 L/V, with a C3 of 8.8 km²/sec², 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

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.
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

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

| 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 \textit{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 | \textit{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 \textit{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)

- Panoramic Camera Assy
- Mechanism Control Electronics
- Transponder
- Avionics
- Mass Spectrometer
- Magnetometer
- Batteries
- Raman/LIBS and Imaging Assy
- Raman/LIBS Laser
- TLS
- ASI
- RF Comm Box
- Backshell/Lander Truss

Probe timeline illustrates configuration changes throughout science mission duration.

- Carrier Flyby Spacecraft
- Probe Entry
- Drop Aeroshell
- Drop Backshell
- Image on Descent
- Land, Surface Rock Analysis

Ring design landing slope capability.

- Dynamic LANDING
- Rock or Block
- Nano Slope
- 30°
- 10°
- 2.5 m Diameter
- 72.7°
- 17°
- 48°
- 30°
- 12°
- 17°
- 48°
- 30°
- 12°

Note: At zenith the carrier S/C is directly overhead of the lander.
Raman/LIBS Survey Measurements and Context Images

Mass Breakdown

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

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

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

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

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)

Compact metallic bellows expand when filled with helium to provide buoyancy.

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

Pressurant Tank with Insulation
Heat Shield
Gondola’s Pressure Vessel
Bellows Carrier Spacecraft
Solar Panels
Top of Gondola (Dome & Lander legs)
Backshell & Parachute

Science Concept of Operations

ASI
NMS
TLS
Imager
Initial Descent
Ascent
Image every ~1.7 km
Transect Imaging

Mag

Carrier Telecom

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Wavelength</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 m HGA mesh</td>
<td>S-band</td>
<td>Probe to Carrier uplink</td>
</tr>
<tr>
<td>2 omni-directional</td>
<td>X-band</td>
<td>Carrier to Earth contingency</td>
</tr>
<tr>
<td>1 m HGA solid</td>
<td>X-band</td>
<td>Carrier to Earth Science</td>
</tr>
</tbody>
</table>

Mass Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>CBE [kg]</th>
<th>Allow [%]</th>
<th>Max Mass [kg]</th>
</tr>
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<tr>
<td>Lander</td>
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<td>Lander Science Payload</td>
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<tr>
<td>Lander Subsystems</td>
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<td>Mechanical/Structure</td>
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<tr>
<td>Mechanisms</td>
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<tr>
<td>Thermal</td>
<td>113</td>
<td>30%</td>
<td>147</td>
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<tr>
<td>Other</td>
<td>34</td>
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<tr>
<td>Bellows</td>
<td>890</td>
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<tr>
<td>Aeroshell</td>
<td>876</td>
<td>30%</td>
<td>1139</td>
</tr>
<tr>
<td>Spacecraft</td>
<td>846</td>
<td>30%</td>
<td>1100</td>
</tr>
<tr>
<td>Satellite (S/C + Probe) Dry Mass</td>
<td>3112</td>
<td>30%</td>
<td>4021</td>
</tr>
</tbody>
</table>

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.
### Venus Flagship Science Themes and Objectives

<table>
<thead>
<tr>
<th>Science Theme</th>
<th>Science Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>What does the Venus greenhouse tell us about climate change?</td>
<td>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.</td>
</tr>
<tr>
<td>How active is Venus?</td>
<td>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.</td>
</tr>
<tr>
<td>When and where did the water go?</td>
<td>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.</td>
</tr>
</tbody>
</table>

### Science Payload for the Design Reference Mission

<table>
<thead>
<tr>
<th>Orbiter</th>
<th>2 Balloons</th>
<th>2 Landers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime (4 years)</td>
<td>(1 month)</td>
<td>Descend Phase (1-1.5 hour)</td>
</tr>
<tr>
<td>InSAR — Interferometric Synthetic Aperture Radar</td>
<td>ASI — Atmospheric Science Instrument (pressure, temperature, wind speed)</td>
<td>Vis-NIR Imaging Spectrometer</td>
</tr>
<tr>
<td>Vis-NIR Imaging Spectrometer</td>
<td>GC/MS — Gas Chromatograph / Mass Spectrometer</td>
<td>Neutral Ion Mass Spectrometer</td>
</tr>
<tr>
<td>Sub-mm Sounder</td>
<td>Vis-NIR camera</td>
<td>Magnetometer</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>Magnetometer</td>
<td>Net Flux Radiometer</td>
</tr>
<tr>
<td>Langmuir Probe</td>
<td>Radio tracking</td>
<td>Nephelometer</td>
</tr>
<tr>
<td>Radio Subsystem (USO — Ultra Stable Oscillator)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Mission Elements

#### Orbiter S/C
- **Launch Vehicle**: Atlas V-551 (w/ 5-m diameter fairing)
- **Mass (CBE + Cont.):** 6308 kg (wet); 2275 kg (dry); Payload mass: 260.4 kg
- **Power**: 32 square meter solar panels (6668 W EOL)
- **Telecom**: 4-m Ka/X-band (Orbiter-to-Earth to 34-in 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 XS-band HGA (Orbiter-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

#### 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
- **Balloons 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-SOC2) primary batteries (10.5 kWh, 22 kg)
- **Telecom**: S-band to Orbiter (w/ backup to carrier flyby st/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 LV (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 LV (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 jetisoned;
    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)
- Ex Officio:
  - Ellen Stefan (VEXAG Chair)
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- Eric Chassefiere (France)
- Anthony Colaprete (NASA ARC)
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- Tibor Balint (JPL)
- Craig Peterson (JPL)
- Alexis Benz (JPL)
- Team-X Design Team