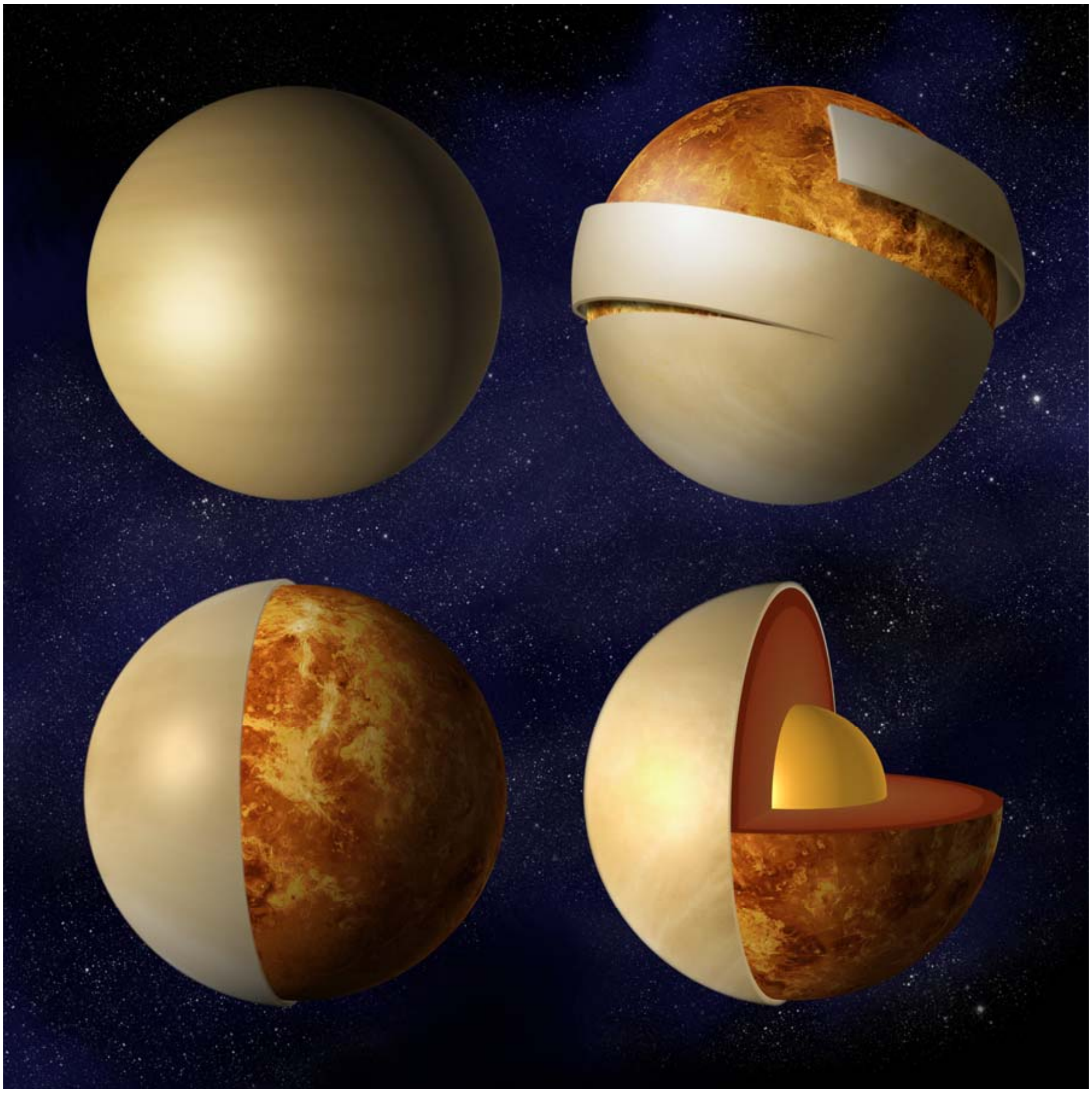
Venus Exploration Themes

August 2014



Prepared in order to preserve extracts from the March 2012 *Venus Exploration Goals and Objectives* and the October 2009 *Venus Exploration Pathways* documents.

TABLE OF CONTENTS

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.

VENUS EXPLORATION THEMES

Foreword

As noted on the top of the previous page, this document was prepared to preserve various diverse extracts from the March 2012 *Venus Exploration Goals and Objectives* and the October 2009 *Venus Exploration Pathways* documents. Section 1 (Fifty Years of Venus Missions) provides a listing of past, current and planned Venus missions from 1961 to the 2020s. Section 2 (Venus Exploration Vignettes) provides one-page overviews of various aspects of Venus exploration. Section 3 (Current and Future Non-US Venus Missions) provides overviews of European Venus Express, Japanese Akatsuki, and Russian Venera-D missions. Section 4 (U.S. Venus Missions Concepts) provides overviews of the Venus Flagship mission concept developed by the Venus Science and Technology Definition Team in 2008–2009 [1], as well as the three Venus mission concepts developed for the Inner Planets Panel of the Planetary Science Decadal Survey [2] in 2010. Section 5 (Venus Laboratory Measurements) provides a table of desirable laboratory measurements as well as a table of current Venus environmental laboratory test facilities.

1. Fifty Years of Venus Missions

There are many reasons to explore Venus. To provide a context for future Venus exploration, Table 1-1 provides an overview of the past, current, and future Venus missions that have been performed or planned by the Russian, European, Japanese, and American space agencies. The Russian space program in 1961 initiated an extensive program for the exploration of Venus, which included atmospheric probes, landers, orbiters, and balloon missions. This produced many successful missions, which provided information on how to survive and conduct experiments in the Venus environment. The Venera 1 impactor was the first spacecraft intended to land on another planet. The Venera 13 lander survived on the surface for 127 minutes, which is still unmatched by any other spacecraft at Venus. The Vega balloons demonstrated the ability of balloons for aerial exploration. The Russians are now pursuing a Venera D mission with an orbiter, a Vega-style lander, a long-lived surface station, and a sub-satellite for launch in 2023 or possibly 2021.

U.S. Venus exploration commenced in 1962 with the flyby of the Mariner 2 spacecraft. Following this, U.S. missions conducted an exploration of the atmosphere and the surface of Venus. In the late 1970s, NASA conducted the orbiter/multiprobe Pioneer–Venus mission, with the objective of understanding the atmosphere of the planet. Magellan in the early 1990s mapped 98% of the surface of the planet, as described in Vignette 1 in Section 2.

Today, Europe's Venus Express orbiter is providing significant science contributions to the understanding of Earth's sister planet by measuring atmospheric dynamics and structure; composition and chemistry; cloud layers and hazes; radiative balance; the plasma environment and escape processes; and, to a certain extent, surface properties and geology through remote sensing, as described in Vignettes 4 and 5. Another orbiter, Japan's Akatsuki (Planet-C, Venus Climate Orbiter, VCO), failed to achieve orbit at Venus on December 7, 2010; and it is now in orbit around the Sun with an orbital period of about 200 days. At this solar orbital period that is just 10% shorter than that of Venus; Akatsuki will encounter Venus again and perform an orbit insertion in 2016–2018, after 11 revolutions around the Sun.

Table 1-1. Summary of Past, Present, and Future Venus Missions.

Spacecraft	Launch Date	Type of Mission
Venera 1	1961	Flyby (intended); telemetry failed 7 days after launch
Mariner 2	1962	Flyby; first to fly by Venus (U.S.)
Zond 1	1964	Probe and main bus; entry capsule designed to withstand 60 to 80°C / 2 to 5 bars
Venera 2 & 3	1965	Probe and main bus; entered the atmosphere of Venus; designed for 80°C / 5 bar
Venera 4	1967	Stopped transmitting at 25 km; 93 minutes descent; first to descend through the atmosphere; designed for 300°C / 20 bar (Russia)
Mariner 5	1967	Flyby (US)
Venera 5	1969	Lander; stopped transmitting at ~20 km (320°C / 27 bar); 53 min descent (Russia)
Venera 6	1969	Lander; stopped transmitting at ~20 km (320°C / 27 bar); 51 min descent (Russia)
Venera 7	1970	First to transmit data from the surface; parachute failure, rough landing, landed on the side; 55 min descent / 23 min on surface (Russia)
Venera 8	1972	Performed as designed; soft-lander; 55 min descent / 50 min on surface (Russia)
Mariner 10	1973	Flyby en route to Mercury (US)
Venera 9	1975	Orbiter and lander; first to return photos of surface; 20+55 min descent / 53 min on surface (Russia)
Venera 10	1975	Orbiter and lander; 20+55 min descent / 65 min on surface (Russia)
Pioneer-Venus 1	1978	Orbiter with radar altimeter; first detailed radar mapping of surface (U.S.)
Pioneer-Venus 2	1978	Four hard-landers (U.S.)
Venera 11	1978	Flyby, soft-lander; 60 min descent / 95 min on surface (Russia)
Venera 12	1978	Flyby, soft-lander; 60 min descent / 110 min on surface (Russia)
Venera 13	1981	Orbiter, soft-lander; first color images of surface; 55 min descent / 127 min on surface (Russia)
Venera 14	1981	Orbiter, soft-lander; 55 min descent / 57 min on surface (Russia)
Venera 15 & 16	1983	Orbiter with a suite of instruments, including radar mapper and thermal IR interferometer spectrometer (Russia)
Vega 1 & 2	1984	Flyby, atmospheric balloon probe (Russia / International)
Magellan	1989	Orbiter with radar mapper (mapped 98% of the surface); first high-resolution global map of Venus (U.S.)
Venus Express	2005	Orbiter with a suite of instruments – ongoing mission (European Space Administration, ESA)
Akatsuki	2010	Venus orbit insertion failed in December 2010; a possible return to Venus in 2016–2018 and perform an orbit insertion (Japanese Aerospace Exploratory Agency, JAXA)
Venera-D	2023 or possibly 2021	Orbiter with Vega-style lander, a long-lived ground station and sub-satellite (Russia)

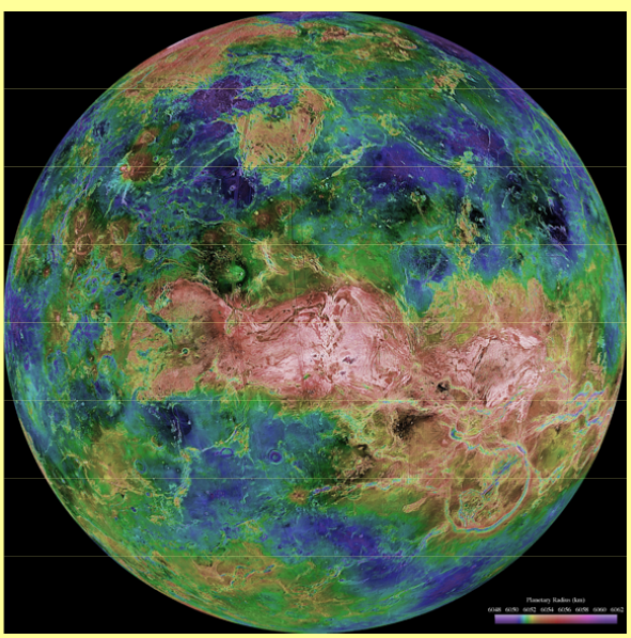
2. Venus Exploration Vignettes

Vignette 1: Magellan

The Magellan spacecraft was launched May 4, 1989, and arrived at Venus on August 10, 1990. The Magellan synthetic aperture radar (SAR) mapped 98% of the Venusian surface with a resolution of about 100 m. Global altimetry and radiometry observations also measured surface topography and electrical properties. A global-gravity map was obtained after Magellan's aerobraking to a circular orbit. This aerobraking paved the way for several future missions. The Magellan mission ended in October 1994 with a controlled entry into the Venusian atmosphere.

Magellan SAR images confirmed that an Earth-like system of plate tectonics does not operate on Venus, most likely due to the lack of surface water. Volcanism characterizes the surface; more than 85% consists of volcanic plains. Two types of highland regions were identified: topographic rises with abundant volcanism interpreted to be the result of mantle plumes, and complexly deformed highland regions called tessera plateaus, hypothesized to have formed over mantle upwellings or downwellings. The gravity field is highly correlated with surface topography, with some highland regions apparently supported by isostatic compensation and others by mantle plumes. Erosion of the surface is not significant due to the lack of water, although some surface modification by wind streaks was seen.

The biggest surprise revealed by the Magellan mission was the crater population of Venus, which is randomly distributed and largely unmodified. Although resurfacing in the last 500 million to one billion years has obscured the impact history of Venus (particularly when compared to the Moon, Mars, and Mercury), the mean surface age is estimated to be ~500 million to one billion years. A debate has ensued over whether the entire surface was resurfaced in a catastrophic event approximately 500 million years ago, or if it was resurfaced more slowly over time. Understanding the history of the surface is important not only for constraining the interior evolution of Venus, but also for the evolution of the atmosphere. While Magellan unveiled Venus, the data returned did not answer the question of why Venus and Earth have followed such different evolutionary paths. However, Magellan data provide a basis for a new set of specific scientific investigations, which will help constrain how habitable planets evolve.



Magellan Radar Mosaic. Blues and greens are the lower plains areas; whites are the rugged highlands.

Vignette 2: Lessons Learned from Pioneer Venus Orbiter and Huygens

Pioneer Venus Orbiter 1978–1992. Venus orbiter with comprehensive payload for remote sensing and in situ aeronomy.

1. Showed that the greenhouse effect operates much more efficiently on Venus. Data from the four atmospheric probes led to a greenhouse model that closely matches the observed vertical temperature profile.
2. Measured long-term changes in atmospheric minor constituents above the clouds. These indicate forcings on decades-long timescales. Possible causes are volcanic activity and variable dynamics of the middle atmosphere.
3. Measured upper atmosphere's response to solar cycle.

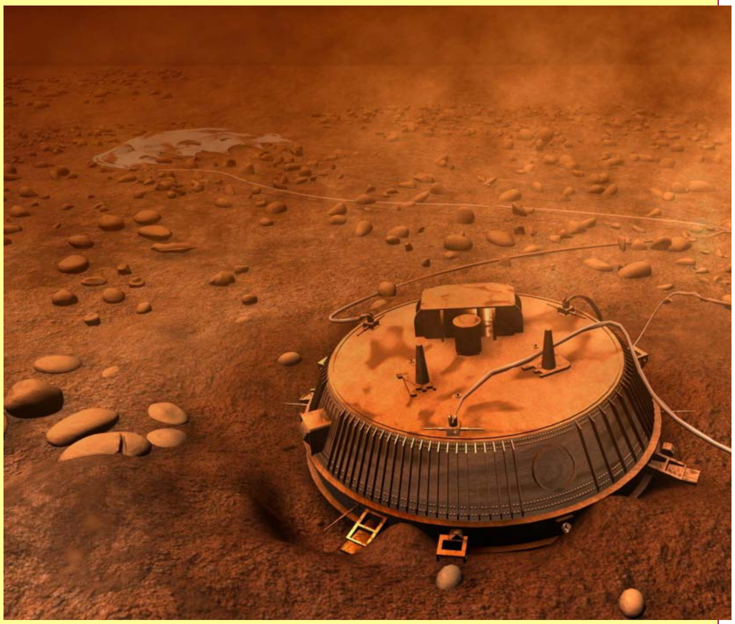
Pioneer Venus demonstrated the need to examine the long-term stability of the current climate and to probe all altitudes during an entire solar cycle. In addition, the nature of the middle and deep atmosphere remains to be examined via remotely sensed spectral signatures or long-duration in situ probes.

Huygens 2005. Titan lander with cameras, spectrometers, and in situ atmospheric and surface science instruments.

1. Huygens provided vertical resolution and sensitivity impossible from remote sensing by the Cassini orbiter, thus providing direct measurements of wind and chemical profiles from >200 km altitude down to the surface and measurement of volatiles entrained within surface materials.
2. Huygens descent images, when combined with other remote observations, allowed identification of dune fields by their distinctive color. This, in turn, yielded the exact lander location and ground truth for remote sensing as well as provided regional context for the landing-site measurements.

Also, radar identification of fields of linear dunes on Titan allowed comparisons to similar features on Earth, Venus, and Mars. Comparisons to Earth analogs have increased understanding of surface processes on both bodies.

Pioneer Venus Orbiter and Probes



Artist's concept of Huygens Probe. Courtesy of ESA.

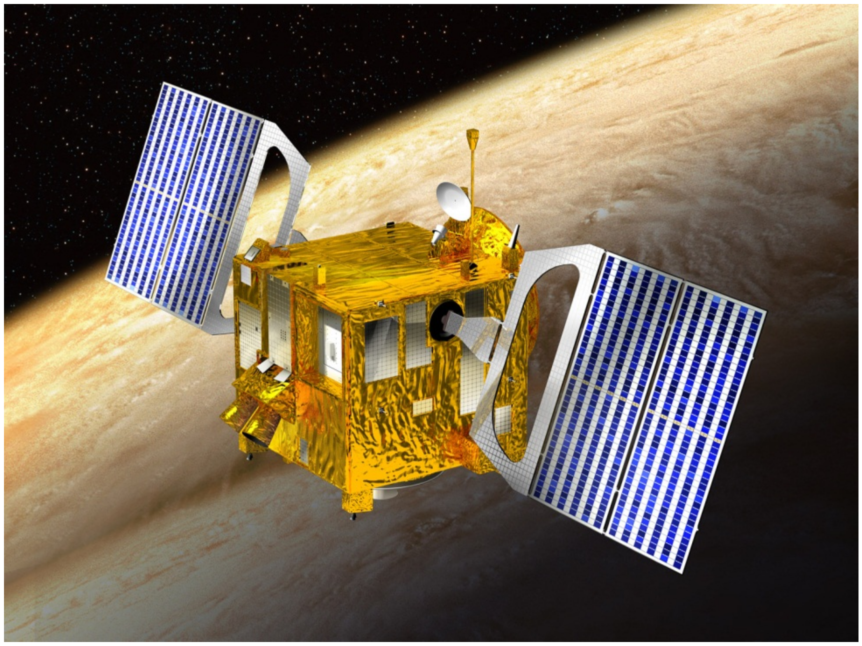
Vignette 3: Venus Express: Revealing the Mysteries of a Neighboring World

Circling the planet once per Earth day since arriving in April 2006, ESA's Venus Express is the first mission to comprehensively explore the entire globe of our sister world from the ground up through the mesosphere, thermosphere, ionosphere, and into space. In particular, Venus Express is the first Venus orbiter to utilize the new tool of nighttime near-infrared spectroscopic imaging to regularly map the structure and movement of clouds and gases in the hostile depths of Venus below the obscuring upper-level clouds, thereby obtaining new insights into the planet's enigmatic circulation, dynamic meteorology, and complex chemistry. This novel spectroscopic tool—embodied on Venus Express as the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS)—maps both (1) the structure and movement of clouds at three different levels (~50-km altitude on the nightside, and 59- and 70-km altitude on the dayside), and (2) the abundances of a plethora of chemically reactive species, including water (H_2O), sulfur dioxide (SO_2), carbon monoxide (CO), and OCS—at a variety of altitudes in the deep atmosphere below the clouds. It also observes the hot (~740 K) surface of Venus near 1µm wavelength, mapping thermal emissions from the ground, which can be used to constrain 1µm surface emissivity and composition as well as to search for and characterize active volcanic processes, as evidenced by locally elevated thermal temperatures and enhanced trace-gas abundances.

Further information from the surface comes from a bistatic-radar experiment that utilizes the spacecraft's communication-radio system to reflect signals off the surface toward Earth. As one facet of the Venus Radio Science experiment (VeRa), these echoes of Venus are then intercepted by NASA's Deep Space Network (DSN) to reveal characteristics of Venus' surface texture and emissivity at cm wavelengths. VeRa also utilizes radio-occultation techniques to measure the vertical profile of Venus' temperature, density, and pressure down to ~36-km altitude over a large range of latitudes, thereby providing detailed information on the planet's 3-D temperature structure, thermal winds, and vertical wave properties. The Venus Monitoring Camera (VMC) images the upper-level clouds in the UV and near-IR at 0.36 and 0.94 µm wavelength, thus providing high-spatial resolution imagery (better than 1-km resolution) of the wave and cell structures of Venus's clouds, as well as providing detailed movies of their motions. Long exposures by this experiment of Venus' night side can be used to search for lightning.

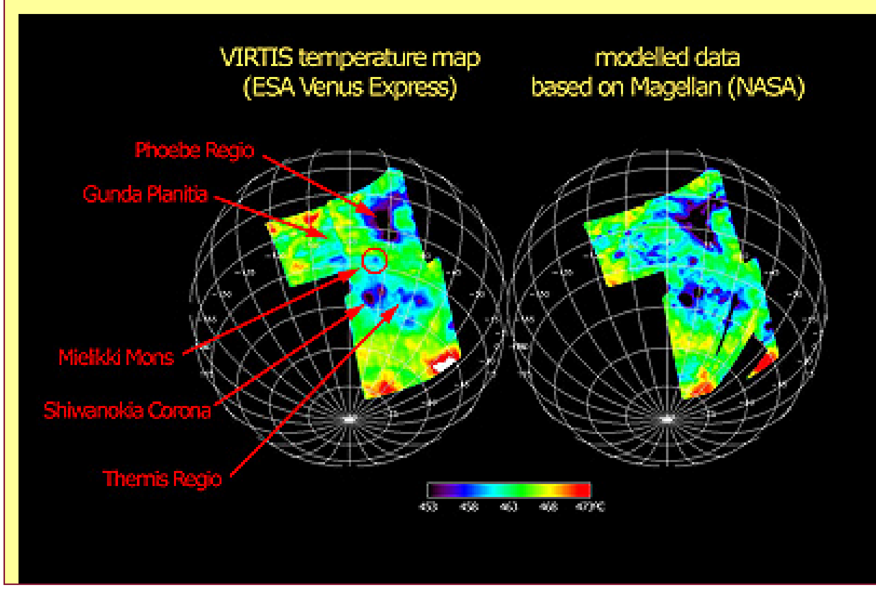
Venus Express also scrutinizes the upper atmosphere of Venus above the clouds. Dual UV and near-IR spectrometers, SPICAV and SOIR, regularly observe the limb of the planet in solar occultation from close range (typically less than 1000 km), thereby producing high-resolution (~5-km) vertical profiles of a variety of light-absorbing species, including H_2O, CO, and SO_2. VIRTIS observes nighttime emissions produced by the recombination of photochemically generated oxygen atoms into oxygen molecules, thereby revealing key day-to-night circulation flows near the 120-km level. Also, VIRTIS maps the nighttime temperatures of the atmosphere at 5-km vertical resolution from 60 to 90 km, providing constraints on the thermal winds in this region. Enigmatic polar features known as Polar Dipoles at the south and north poles, possible manifestations of the Hadley circulation, can also be mapped in detail and followed in time.

Venus Express also investigates the planet's ionosphere and near-space environment. The Analyser of Space Plasmas and Energetic Atoms (ASPERA) measures the solar wind as it streams around Venus, assessing the number density and speed of protons ejected from the Sun. A magnetometer experiment (MAG) measures the local magnetic field produced by ionization of Venus' upper atmosphere by both intense UV sunlight and solar wind. Joint measurements by ASPERA and MAG from a variety of positions around Venus then reveal how Venus interacts with the Sun's magnetosphere and solar wind. ASPERA also measures ionized atoms such as hydrogen and oxygen ejected from the planet's tenuous uppermost atmosphere by the solar wind, thus providing constraints on the loss of atmospheric elements responsible for the extremely dry state of Venus today. Venus Express has generated more than 1 Terabit of data to Earth in its first 500 days of operation. Recent Venus Express VIRTIS results are given in Vignette 5.



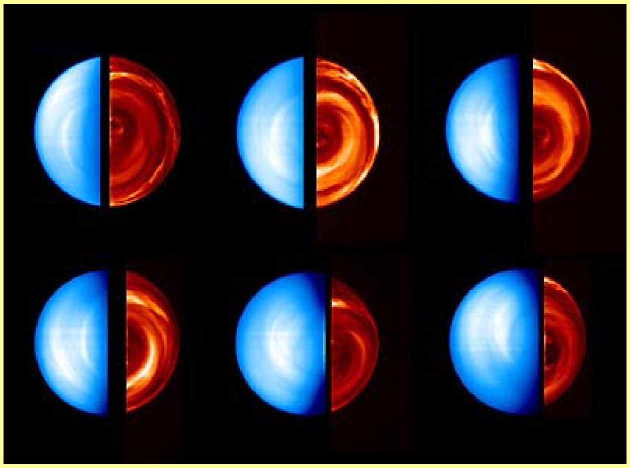
Artist's concept of Venus Express spacecraft operating at Venus since 2006. Courtesy of ESA.

Vignette 4: Venus Express VIRTIS Results

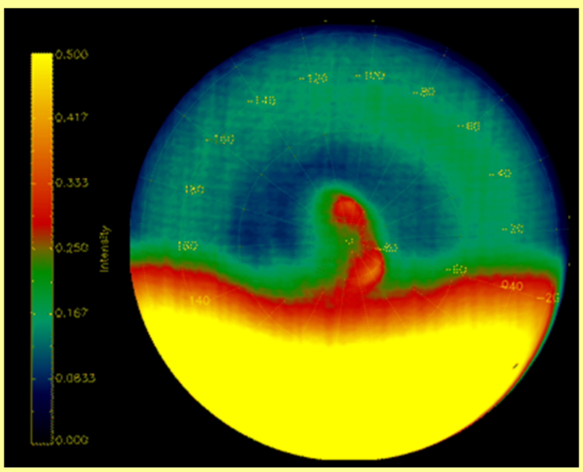


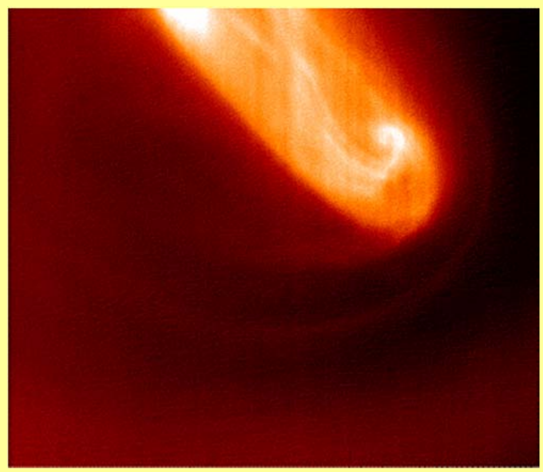
Surface Temperatures. (left) Black-body temperatures measured for the surface correlate well with topography (right), due to decreases of surface temperature with height. Slight variations in this correlation may indicate differences in the surface rock emissivities. (Courtesy of ESA.)

Vignette 4: Venus Express VIRTIS Results (continued)



Day and night images of the South Pole of Venus. Daytime images (left side of each image) show high-altitude clouds of small particles near the 70-km level. Night images (right side of each image) show thick clouds of relatively large particles near the 50-km level. Clouds at night are seen in silhouette against the glow of Venus' hot lower atmosphere, using near-infrared thermal radiation near 1.7-µm wavelength. Following the dark (cloudy) and bright (less cloudy) regions, as they move around the planet, yields measurements of Venus' winds near the 55-km level. Comparison with 70-km altitude winds as measured by the movements of dayside clouds yields wind shears, providing clues to the processes powering Venus' enigmatic system of super-rotating winds.





Polar Vortex Phenomena. Venus Express confirmed that the Venusian South Pole has a complex and variable vortex-like feature, sometimes taking the shape of a dipole, but at other times morphing into tripolar, quadrupolar, and amorphous, indistinct shapes. Temperatures near the 60-km level are shown in the nighttime portions of 5-µm images, revealing the dipole to be notably hotter than its surroundings, likely due to compression of descending air. (Bottom left image, taken in daytime conditions, is overexposed by the Sun). Right-hand, close-up image shows filamentary nature of the dipole, which changes shape constantly in the dynamically active atmosphere. The dipole is offset from the pole by several degrees of latitude and rotates with a period of about 2.4 days.

3. Current and Future Non-U.S. Venus Missions

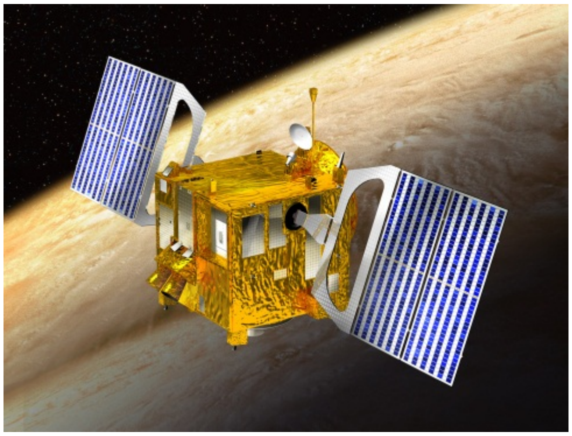
ESA's Venus Express orbiter mission continues to be the only mission studying Venus at present. The mission has been officially extended through December 2014 by ESA. The spacecraft continues to function well with the project exploring aerobraking operations and new science from a shorter orbit in 2014. Future observations of Venus may be provided by the Japanese Akatsuki and the proposed Russian Venera-D missions.

3.1. Europe's Venus Express Mission

Venus Express is the first Venus exploration mission of the European Space Agency and was built using spare 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 objectives of the mission are the long-term observations of the Venusian atmosphere. Such long-term observations have never been accomplished in previous missions to Venus, and are a 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 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.

3.2. Japan's Akatsuki Mission

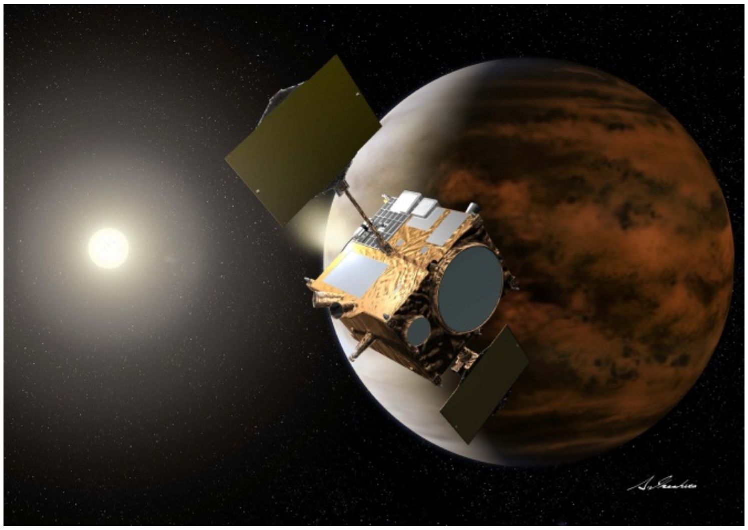
Akatsuki (aka PLANET-C and Venus Climate Orbiter) is a Japanese mission to study the atmosphere of Venus. Akatsuki was designed to enter an elliptical orbit, with pericenter and apocenter of 300 to 80,000 km respectively, and an orbital period of 30 hours. This enables a partial synchronization with the super-rotation of the Venusian atmosphere. Thus, Akatsuki will observe the same cloud patterns for consecutive orbits. Akatsuki is 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 three 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 four 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 November 2015 and attempt an orbit insertion in 2016.

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.



Artist's concept of Japan's Akatsuki, Venus Climate Orbiter at Venus (Courtesy of JAXA)

3.3. *Russia's Venera-D Mission*

Based on a presentation made at the 4th Moscow Solar System Symposium, October 2013, the Venera-D (Венера-Д) mission development is underway with a Phase-A study for a Venus mission to be launched in 2020 or 2023. This would consist of an orbiter, VEGA-style lander, a long-lived surface station and a sub-satellite. Technical specification of the long-living station has been developed. It was found that with the presently available technology, using silicon electronics, the lifetime of a 100-kg station on the surface of Venus is limited to 24 hours. The possibility of installing seismology, meteorology, and imaging experiments was studied. The data rate of 10 kb/s (transmission to orbiter or to balloon) or 10 b/s (transmission direct-to-Earth) may be achieved. The sub-satellite utilizes signal from the Earth-based emitting antenna, which is recorded by three (L, S, and X band) receivers onboard the orbiter and sub-satellite for conducting five radio science experiments. The sub-satellite-Venus occultation period is expected to last up to about one hour. The five experiments are:

1. Interplanetary environment
2. Ionosphere: via two-band radio occultations
3. Atmosphere: via two-band radio occultations
4. Bistatic radar sounding of the near surface atmosphere
5. Radar sounding of the surface

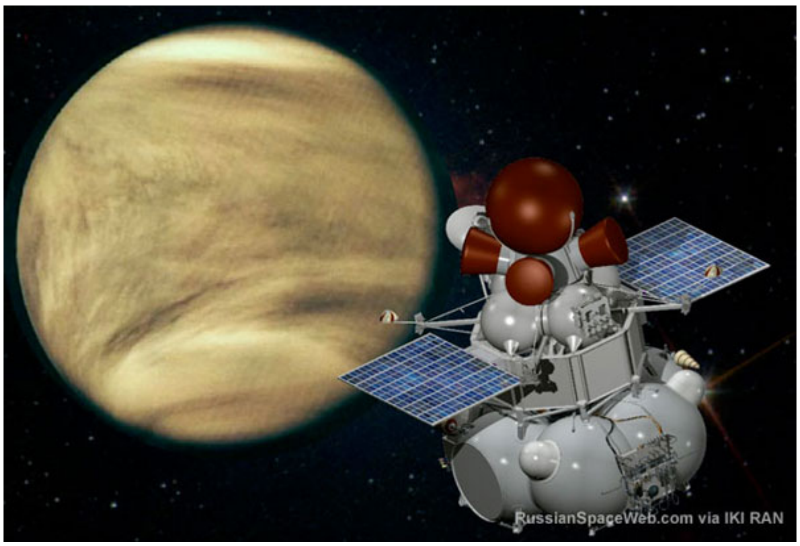
Scientific Goals are:

- Investigation of the structure and chemical composition of the atmosphere, including abundances and isotopic ratios of the light and noble gases;
- Thermal structure of the atmosphere, winds, thermal tides and solar locked structures;
- Clouds, structure, composition, microphysics, chemistry;
- Chemical analysis of the surface material, study of the elemental composition of the surface, including radiogenic isotopes;
- Study of interaction between the surface and atmosphere, search for volcanic and seismic activity; search for lightning;
- Study of the dynamics and nature of superrotation, radiative balance and nature of the enormous greenhouse effect;
- Investigation of the upper atmosphere, ionosphere, electrical activity, magnetosphere, and escape rate.

Mission Elements are:

- Orbiter (Phobos-Grunt design) in a 24-hour polar orbit, lifetime > 3 years
- Lander (VEGA-type design) 2–3 hours on the surface
- Long living station, 24 hours on the surface
- Sub-satellite, with 48-, 24-, or 12-hour orbit being considered

Overview of Venera-D mission elements; orbiter, sub-satellite , long-lived surface station, and lander



Artist's concept of the Venera-D orbiter

Strawman Venera-D Instrumentation would consist of:

Main Orbiter:

- Fourier interferometer-spectrometer (5–40 μm), ν = 250–2000 см$^{-1}$, $\Delta\nu$ = 1 cm^{-1}
- Solar and star occultation UV spectrometer (0.1–0.3 μm) and IR (2–4 μm)
- Millimeter radio-wave sounder λ =3–10 mm
- UV-mapping spectrometer λ = 0.2–0.5 μm, Δ λ = 0.0004 μm
- IR-mapping spectrometer λ = 0.3–5.2 μm, Δ λ = 2.4 nm
- Multispectral monitoring camera
- Radio science (L, S, and X bands)
- Plasma package
- High-resolution heterodyne spectrometer ($\lambda / \Delta\lambda$ = 10^8), λ= 1.4 - 1.6 and 7 - 11 μm

Sub-Satellite:

- Plasma package
- Radio science

Venera-D Lander Payload:

- Active gamma and neutron spectrometer
- Gas chromatography–mass spectrometer
- Mossbauer spectrometer
- TV cameras (landing, stereo, and panoramic, high res. up to 0.1 mm)
- Multi channel tunable diode laser spectrometer
- Nephelometer-particles counter
- Wave-package
- Optical package
- Radio-science
- Seismometer
- Atmosphere and surface sampling devices

The final Venera-D scientific payload will be determined pending the participation of and contributions from the international space agencies. The mission is being proposed to the Russian government for its 2015–2025 Exploration Plan.

4. U.S. Venus Exploration Mission Concepts

To understand how the exploration goals and objectives for Venus can be met, it is useful to examine the Venus Flagship mission concepts defined by the Venus Science and Technology Definition Team (STDT) study [1], as well as those described in the Planetary Science Decadal Survey [2].

4.1. Venus Flagship-Class Missions

In addition to the PI-led Discovery and New Frontiers missions described in the Venus Exploration Roadmap [3], 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 the comprehensive studies of planetary bodies, such as those undertaken by the Voyagers, Galileo, Cassini, and the Mars rovers. These missions generally require large propulsion systems and launch vehicles. In addition, Flagship missions often require extensive trade studies to determine the proper balance of cost, risk, and science return.

In 2008 NASA commissioned a Venus Flagship Mission Study resulting in a Venus Flagship Design Reference Mission, VFDRM just prior to the Decadal Survey. For the notional budgets assigned to Decadal Survey mission concepts, the VFDRM was deemed too ambitious and expensive. Thus, a Venus Climate Mission (VCM) [4], the scaled-down version of the VFDRM, was recommended by the Planetary Sciences Decadal Survey. In addition, the Inner Planets Panel undertook studies of two additional focused missions — a Venus Intrepid Tessera Lander (VITaL) [5] and a Venus Mobile Explorer (VME) [6]. Each of these mission concepts is described below.

4.1.1. Venus Flagship Design Reference Mission (VFDRM)

A Venus Flagship mission study was conducted in 2008–2009 based on recommendations identified by the 2003 *NRC Decadal Survey* and the 2006 *NASA Solar System Exploration Roadmap*. 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 4-1). 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.

The VFDRM mission was 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 spacecraft, one being an orbiter and the other delivering two entry vehicles, where each entry vehicle carries dual landers and balloons (Figure 4-1). In this dual-launch scenario, two Atlas V launches are needed to send these spacecraft to Venus. The first launch vehicle would deliver two landers and two balloons to Venus on a Type-IV trajectory. The second launch vehicle would deliver the orbiter on a Type-II (covering more than 180° around Sun) 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 had completed 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 could 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.

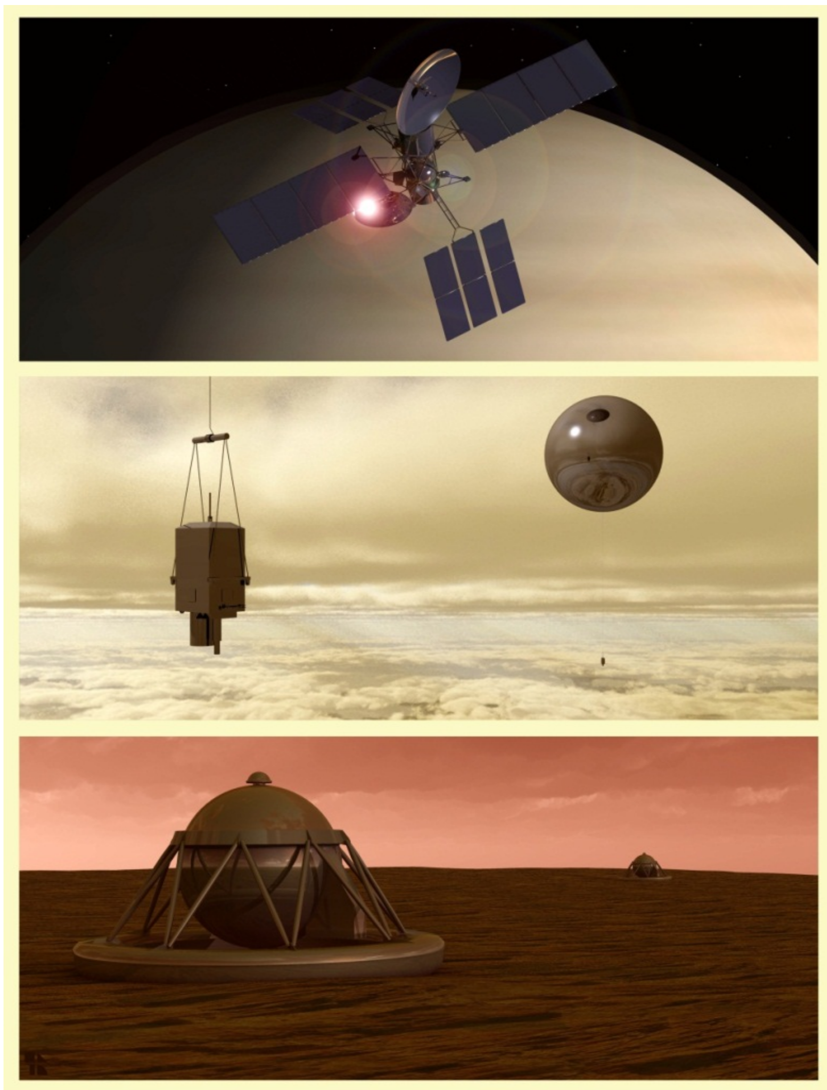


Figure 4-1. Artist's concept of the Venus Flagship Design Reference Mission elements: orbiter, balloons, and landers, developed by the Venus STDT in 2008–2009. Artwork by Tibor Balint.

4.1.2. Venus Climate Mission (VCM)

As noted above, for the notional budgets assigned to Decadal Survey mission concepts, the VFDRM was deemed too ambitious and expensive. Thus, a Venus Climate Mission [4], the scaled-down version of the VFRDM was recommended by the Planetary Sciences Decadal Survey. This Flagship mission would 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 mission, advocated by the Decadal Survey, focuses on the detailed characterization of the surface, deep atmosphere and their interaction, VCM would provide 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, as well as dynamics and chemistry of the Venusian atmosphere. Specific goals include:

- 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 an extensive 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 global climate models. Evidence would 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 mini-probe, gondola/balloon system and two drop sondes 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.

VCM's instrumentation would include:

- Carrier Spacecraft with a Venus Monitoring Camera, at visual and IR wavelengths
- Gondola/Balloon System with:
  - Neutral Mass Spectrometer

  - Tunable Laser Spectrometer
  - Atmospheric Structure Instrumentation
  - Nephelometer
  - Net Flux Radiometer
- Mini-Probe with a Neutral Mass Spectrometer, Net Flux Radiometer, and Atmospheric Structure Instrumentation
- Two Drop Sondes with Atmospheric Structure Instrumentation and Net Flux Radiometer

4.2. Other Decadal Survey Venus Mission Concepts

In addition to the Venus Climate Mission, the Decadal Survey Inner Planets Panel developed two other mission concepts for consideration. These are the Venus Intrepid Tessera Lander (VITaL) [5] and Venus Mobile Explorer (VME) [6] described below

4.2.1. Venus Intrepid Tessera Lander (VITaL)

The VITaL mission concept [5] 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.

4.2.2. Venus Mobile Explorer (VME)

The Venus Mobile Explorer (VME) mission concept [6] 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 (about 3 km above the surface) between the two surface locations, it could offer new, high-spatial-resolution views of the surface at NIR 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 about 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.

5. 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 5-1, 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.

5.1. New Laboratory Studies for Future Venus Exploration

There are four basic physical domains 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 5-1. 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, oxygen and carbon dioxide
	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 chemicals 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 gases	
	Chemical transfer of elements from surface into atmosphere (and onto spacecraft windows?)	

A Venus Environmental Test Facility would enable:

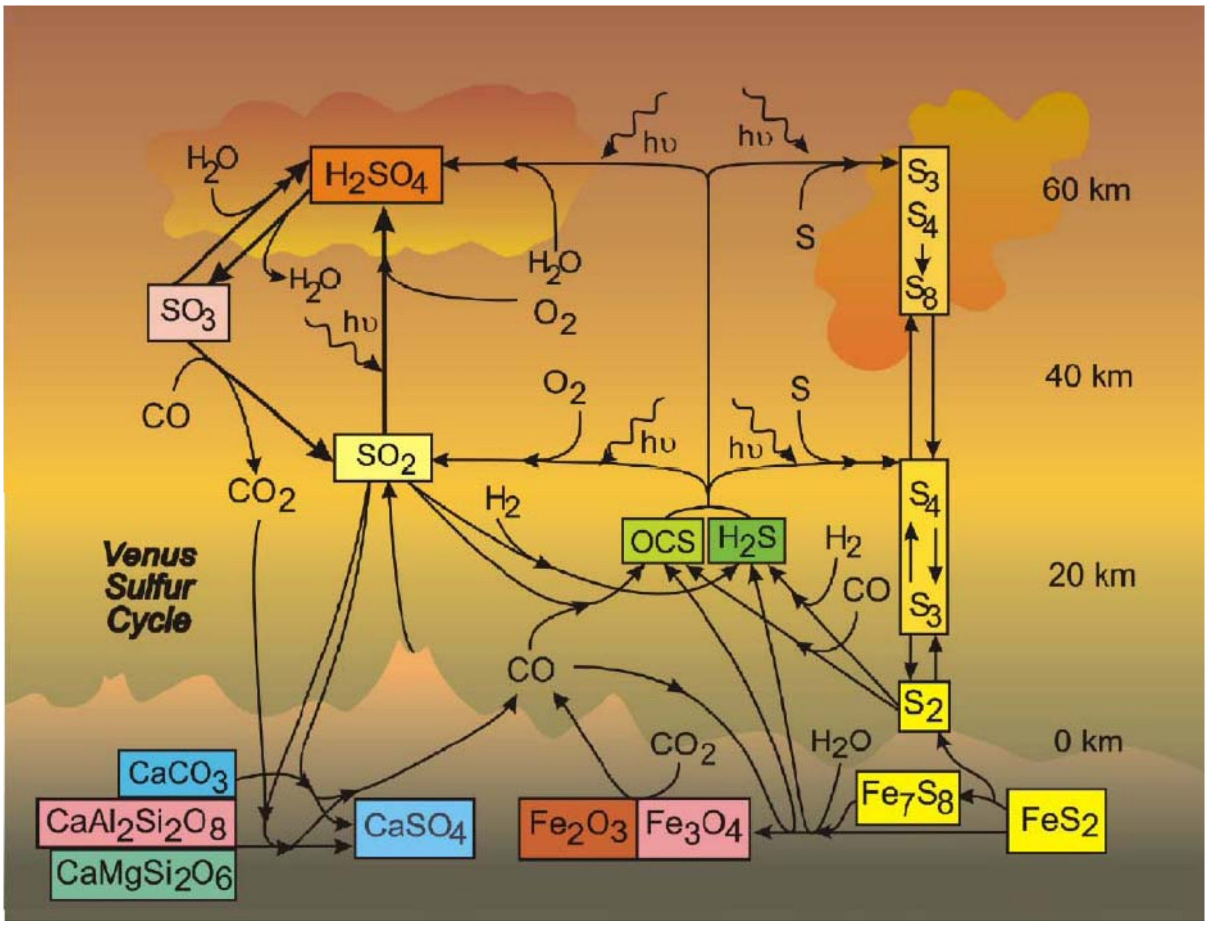
- Understanding the chemistry in the atmosphere above the cloud tops: There is a shortage of laboratory measurements under Venusian atmospheric conditions that would enable accurate determinations of the atmospheric properties. In addition, for understanding what acquired measurements reveal about atmospheric 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: In this region of high temperature and pressure, new laboratory measurements are required of the optical properties of different molecular constituents, including sulfur compounds.
- 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 the reaction rates.

5.2. Current U.S. Test Facilities

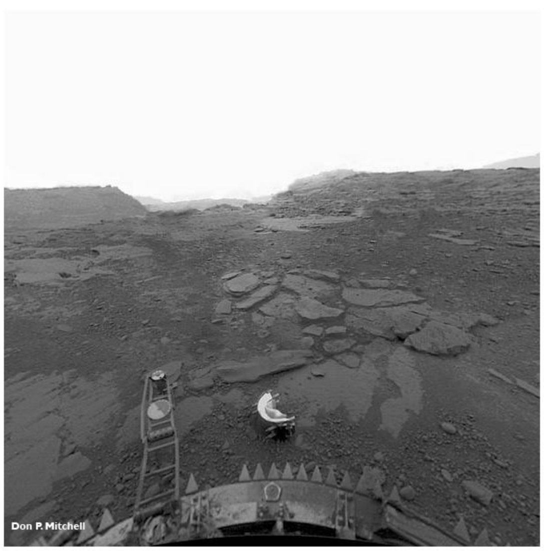
Table 5-2 summarizes the current U.S. environmental test facilities with their volumes, pressures, temperatures, and gas species. Several of these facilities are available via Research Opportunities in Space and Earth Sciences (ROSES) proposals to the Venus Program Executive at NASA Headquarters.

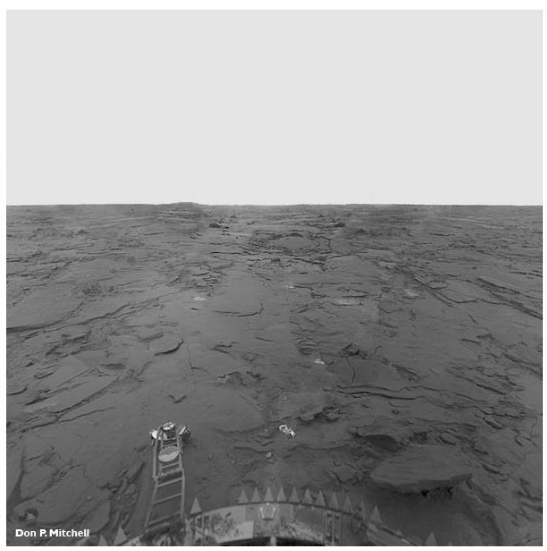


Artist's concept of the chemical reactions taking place in the Venusian atmosphere

Table 5-2. Current U.S. Venus Environmental Test Facilities

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.

6. References

[1] Bullock, M. A. et al.2009. **Venus Flagship Mission Study: Report of the Venus Science and Technology Definition Team,** http://vfm.jpl.nasa.gov/files/Venus+Flagship+Mission+Study+090501-compressed.pdf

[2] Vision and Voyages for Planetary Science in the Decade 2013-2022, Committee on the Planetary Science Decadal Survey, Space Studies Board, Division on Engineering and Physical Sciences, The National Research Council of the National Academies, The National Academy Press, Washington, D.C., www.nap.edu

[3] **Roadmap for Venus Exploration - May 2014**, posted on the VEXAG website http://www.lpi.usra.edu/vexag/

[4]**Venus Climate Mission (VCM) Mission Concept Study Planetary Science Decadal Survey June 2010**, posted on the VEXAG website http://www.lpi.usra.edu/vexag/reports/VCM_report_FINAL.pdf

[5] **Venus Intrepid Tessera Lander (VITaL) Mission Concept Study Report to the NRC Decadal Survey Inner Planets Panel, March 2010**, posted on the VEXAG website http://www.lpi.usra.edu/vexag/reports/VITaL_FINAL_040809.pdf

[6] **Venus Mobile Explorer (VME) Mission Concept Study Report to the NRC Decadal Survey Inner Planets Panel, December 2009**, posted on the VEXAG website http://www.lpi.usra.edu/vexag/reports/VME_FINAL_ITAR_Compliant.pdf

7. Acronyms and Abbreviations

ASPERA	Analyser of Space Plasmas and Energetic Atoms. (Venus Express)
CCD	charge-coupled device
DOE	Department of Energy
DSN	Deep Space Network
ESA	European Space Agency
GSFC	NASA Goddard Space Flight Center
IR	infrared
IR1 and IR2	infrared cameras (Akatsuki)
JAXA	Japanese Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LAC	Lightning and Airglow Camera (Akatsuki)
LANL	Los Alamos National Laboratory
LIBS/RAMAN	Laser-Induced Breakdown Spectroscopy using Raman scattering
LIR	long wavelength infrared camera (Akatsuki)
MAG	Magnetometer Experiment (Venus Express)
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration

NRC	National Research Council
PDS	Planetary Data System
PI	Principal Investigator
PLANET-C	Akatsuki (Japan's Venus Climate Orbiter)
RLVT	Venus Optical Test Facility (JPL)
RS	Radio Science experiment (Akatsuki)
SPICAV–SOIR	Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus –Solar Occultation at Infrared (Venus Express)
STDT	Science and Technology Definition Team
U.S.	United States
UV	ultraviolet
UVI	ultraviolet imager (Akatsuki)
VCM	Venus Climate Mission
VCO	Venus Climate Orbiter (Planet-C, Japan's Akatsuki Mission)
Vega	Russian Halley/Venus Lander and Orbiter Mission
VeRa	Venus Radio science experiment (Venus Express)
VEXAG	Venus Exploration Analysis Group
VFDRM	Venus Flagship Design Reference Mission
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer (Venus Express)
VITaL	Venus Intrepid Tessera Lander
VMC	Venus Monitoring Camera (Venus Express)
VME	Venus Mobile Explorer
VMTF	Venus Materials Test Facility (JPL)

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

ACKNOWLEDGMENTS- ? UPDATE?

Preparation of this document was supported in part through research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.