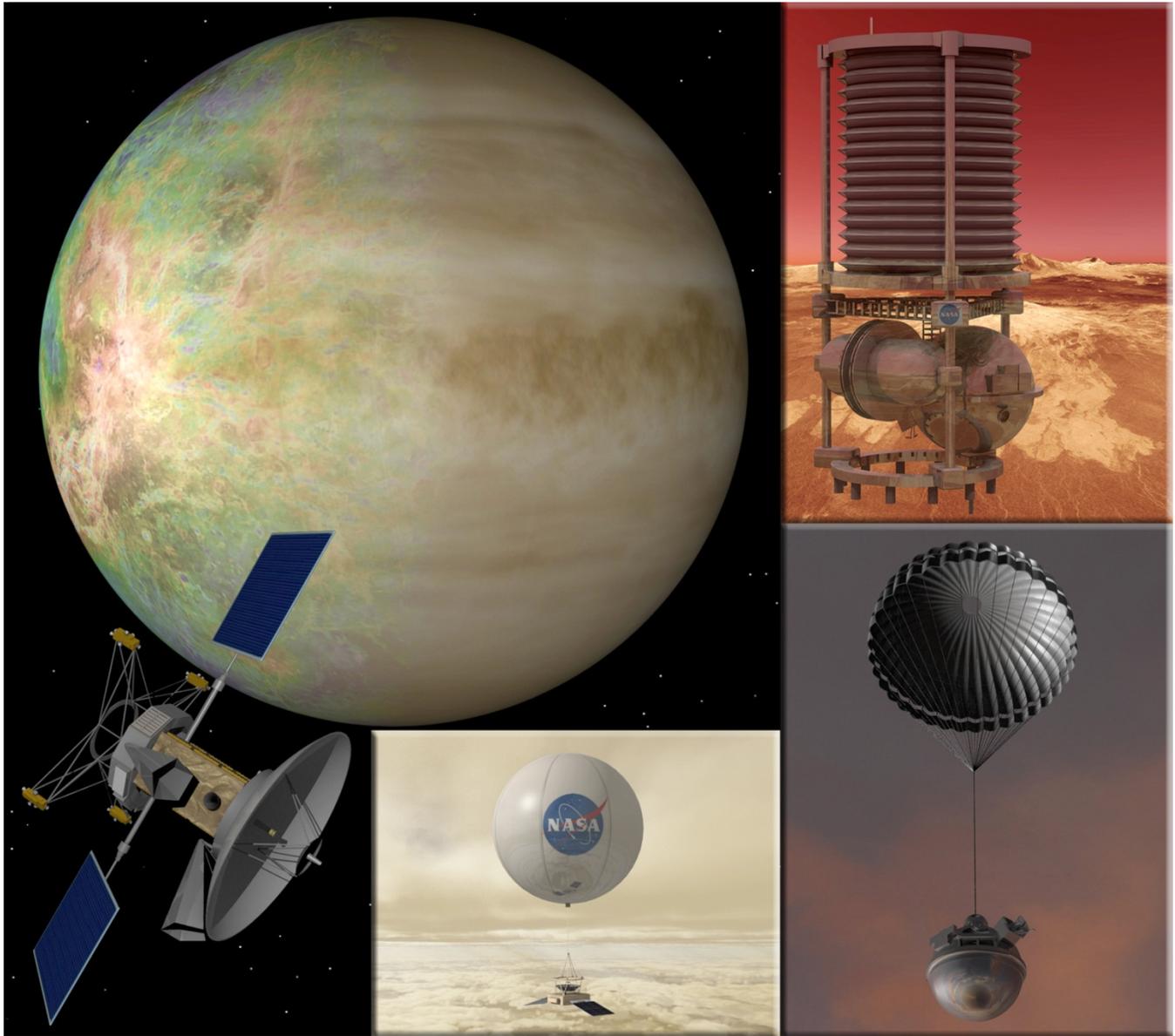


Venus Exploration Themes

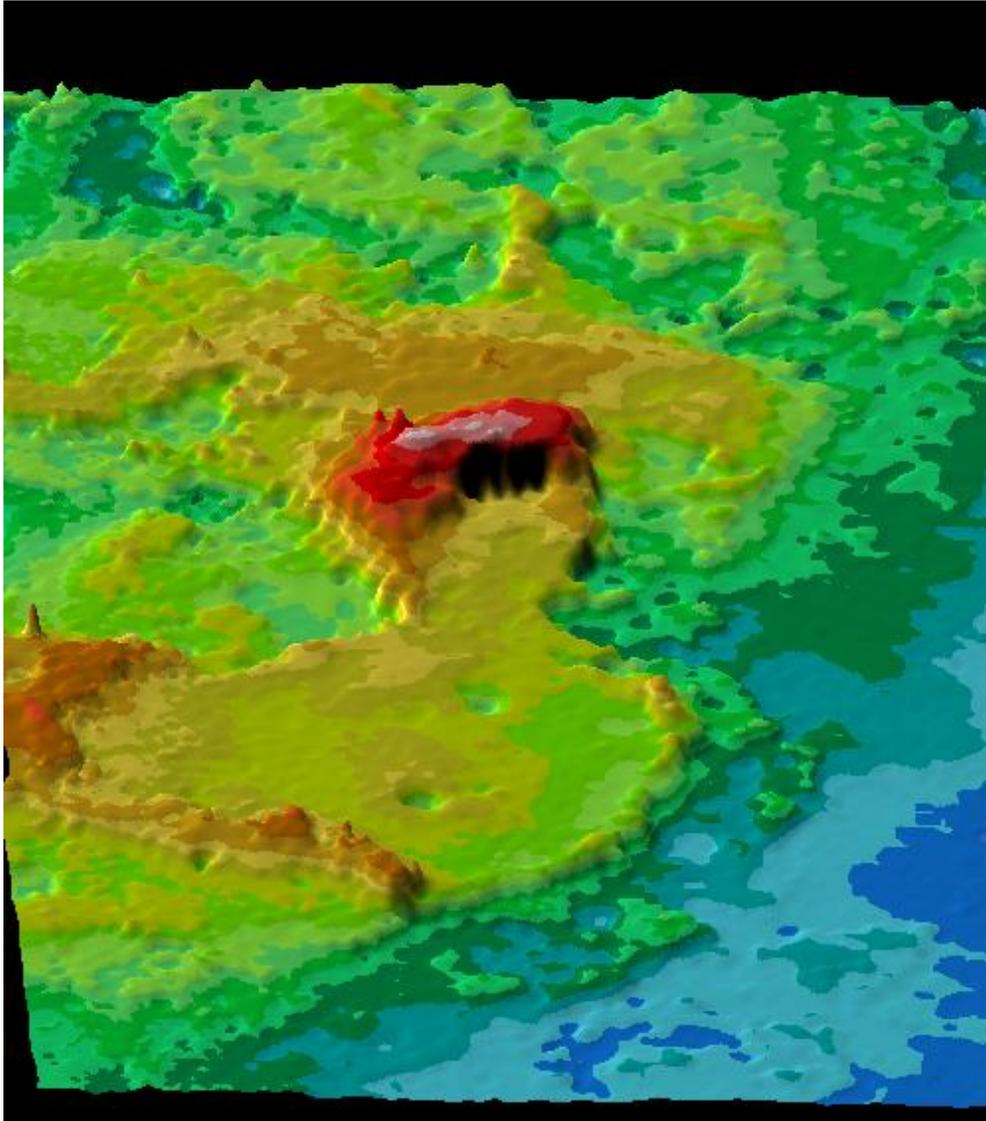
VEXAG Meeting #11

November 2013



VEXAG (Venus Exploration Analysis Group) 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 NASA's Advisory Council, which is open to all interested scientists and engineers, and regularly evaluates Venus exploration goals, objectives, and priorities on the basis of the widest possible community outreach.

*Front cover is a collage showing Venus at radar wavelength, the Magellan spacecraft, and artists' concepts for a Venus Balloon, the Venus In-Situ Explorer, and the Venus Mobile Explorer.
(Collage prepared by Tibor Balint)*



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.

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.

Prepared as an adjunct to the three VEXAG documents: *Goals, Objectives and Investigations; Roadmap*; as well as *Technologies* distributed at VEXAG Meeting #11 in November 2013. This document preserves extracts from the March 2012 *Venus Exploration Goals and Objectives* and the October 2009 *Venus Exploration Pathways* documents.

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ACKNOWLEDGMENTS

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1. Fifty Years of Venus Missions

There are many reasons to explore Venus (Appendix A). To provide a context for future Venus exploration, Table 1 provides an overview of the past, current, and future Venus missions that have been carried out 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 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, 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 seventies, 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.

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. 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 (US)
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)

Spacecraft	Launch Date	Type of Mission
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 (US)
Pioneer-Venus 2	1978	Four hard-landers (US)
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 (US)
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)



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

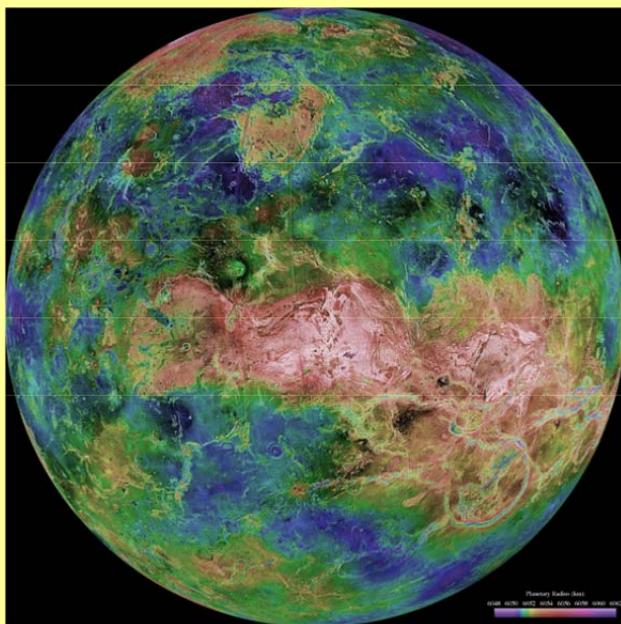
2. Venus Exploration Vignettes

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 not only important for constraining the interior evolution of Venus, but also 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: Experiencing Venus by Air: The Advantages of Balloon-Borne In Situ Exploration

Balloons provide unique, long-term platforms from which to address such fundamental issues as the origin, formation, evolution, chemistry, and dynamics of Venus and its dense atmosphere. As successfully and dramatically demonstrated by Russia's twin Vega balloons in 1985, such aerial vehicles can uniquely measure Venus' dynamic environment in three dimensions, as they ride the powerful, convective waves in Venus' clouds near the 55-km level. Also, by sampling over an extended period, balloons can measure the abundances of a plethora of tell-tale chemical and noble gases, key to understanding Venus' origin, evolution meteorology, and chemistry. While the Vega balloons successfully pioneered the use of aerial platforms to explore planets, weight restrictions prevented their measuring abundances of diagnostic chemicals or noble gases. The new, highly miniaturized instrument technologies of the 21st century allow such measurements to be made.

Our knowledge of the origin, formation, and evolution of all the planets—including Venus—relies primarily on knowledge of the bulk abundances and isotopic ratios of the noble gases—helium, neon, argon, krypton, and xenon—as well as on the isotopic distributions of light gases such as nitrogen. For example, xenon, with its nine tell-tale isotopes, along with krypton (Kr) and argon (Ar) and their isotopes, can together reveal a range of ancient cataclysms on Venus and other planets. These include the nature of (1) any global atmospheric blowoff by intense solar extreme ultraviolet radiation, and (2) any major impacts by large (>200-km diameter) comet-like planetesimals from the outer solar system. On the other terrestrial planets where xenon has been adequately measured—Earth and Mars—one or more such major cataclysmic events occurred early in their histories. Similar measurements for Venus would reveal whether cataclysmic events occurred on our sister planet as well. As these key tell-tale noble elements have no appreciable spectral signature, in situ sampling is the only means by which to measure them. Thus, to reach into the planet's past, one must sample Venus directly, with typical precisions of better than 5% for both isotopic ratios and bulk abundances.

Such detailed and precise isotopic measurements can be more than adequately achieved by today's lightweight balloon-borne instrumentation suspended for several days in the middle atmosphere near an altitude of 55 km. Riding the strong winds of Venus near the Earth-like 297-K, 0.5-bar pressure level, hundreds of high-precision, mass-spectroscopy measurements can be acquired and transmitted during the balloon's two-day transit across the face of Venus as viewed from Earth, thus achieving the requisite tight constraints on isotopic abundances of all the noble gases and many light elements. In addition, vertical profiles of chemically active species can be obtained as the balloon rides the planet's dynamic array of gravity waves, planetary waves, and convective motions, thus providing unique insights into photochemical and thermochemical processes. Additionally, the planet's sulfur-based meteorology can be explored, for example, by measuring over time and altitude both cloud particles and their parent cloud-forming gases, as well as lightning frequency and strength.

As was done by the Vega balloons, both local dynamics and planet-scale atmospheric circulation can be investigated via radio-tracking of the balloon from Earth. Today's improved interferometric and Doppler tracking together with well-calibrated onboard pressure sensors can yield knowledge of all three components of balloon velocity an order of magnitude more accurately than achieved by Vega, that is, better than 10 cm/s on time scales of a minute in the vertical and an hour in the horizontal. Such accuracies can provide fundamental measurements of the amplitude and power of gravity waves and the latitude/longitude characteristics of zonal and meridional winds at known pressure levels. All of these are key to understanding the processes powering Venus' super-rotating circulation.

Beyond providing unique insights into the origin/evolution, dynamics, and chemistry of Venus, exploring Venus by balloon provides valuable experience for flying the skies of other worlds. Experiencing Venus for days and perhaps weeks by the first airborne rovers could well lead to a new era of "aero-roving" the distant skies of Titan and the many gas giants of the outer solar system.

Vignette 3: 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.

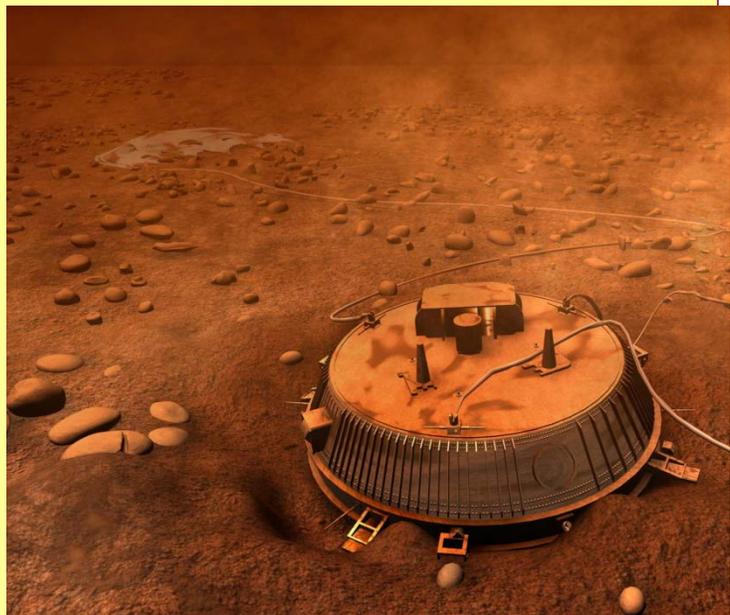
Huygens 2005. Titan lander with cameras, spectrometers, and in situ atmospheric and surface science instruments.

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 in turn have increased understanding of surface processes on both bodies.



Pioneer Venus Orbiter and Probes



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

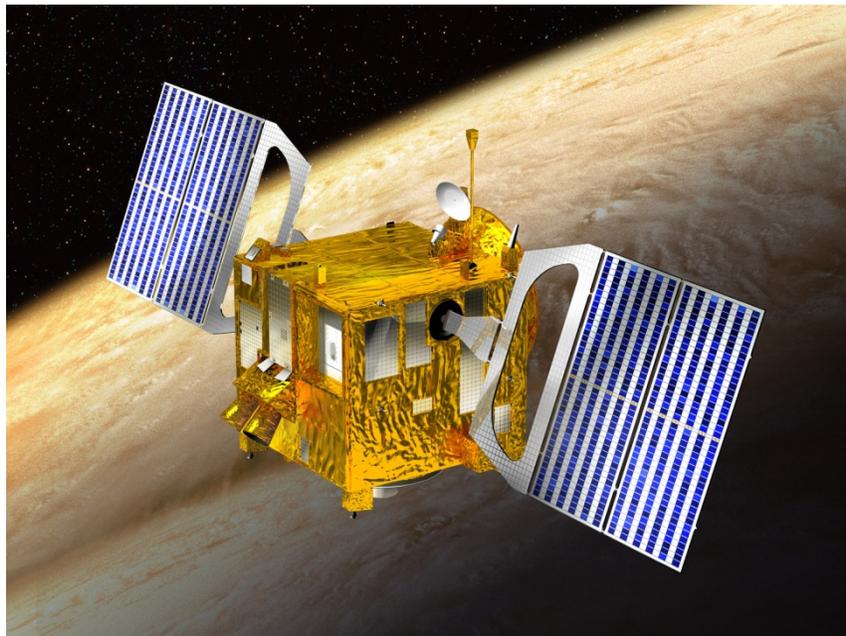
Vignette 4: Venus Express: Revealing the Mysteries of a Neighboring World

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 (H₂O), sulfur dioxide (SO₂), 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 1-micron wavelength, mapping thermal emissions from the ground, which can be used to constrain 1-micron 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 μ m 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.

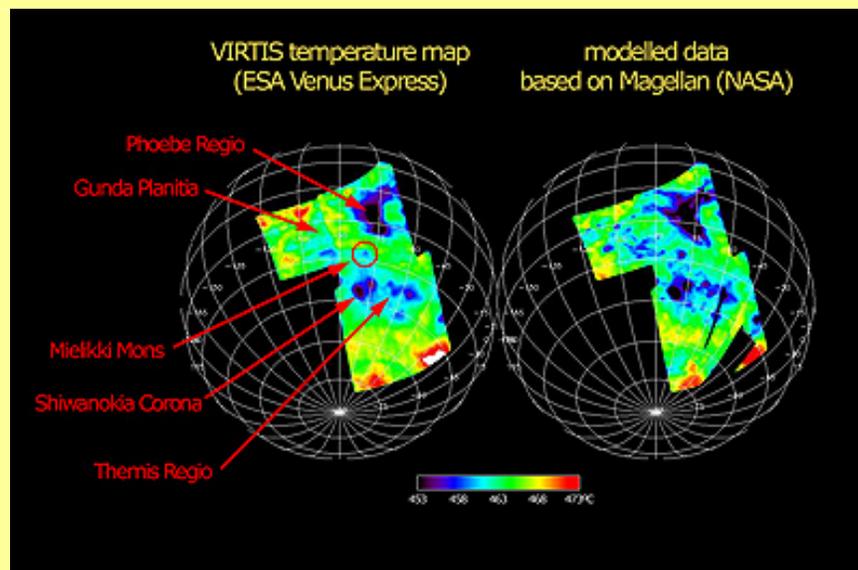
Venus Express also scrutinizes the upper atmosphere of Venus above the clouds. Dual UV and near-IR spectrometers, SPICAV and SOIR, regularly observe the limb of the planet in solar occultation from close range (typically less than 1000 km), thereby producing high-resolution (~5-km) vertical profiles of a variety of light-absorbing species, including H₂O, CO, and SO₂. 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.



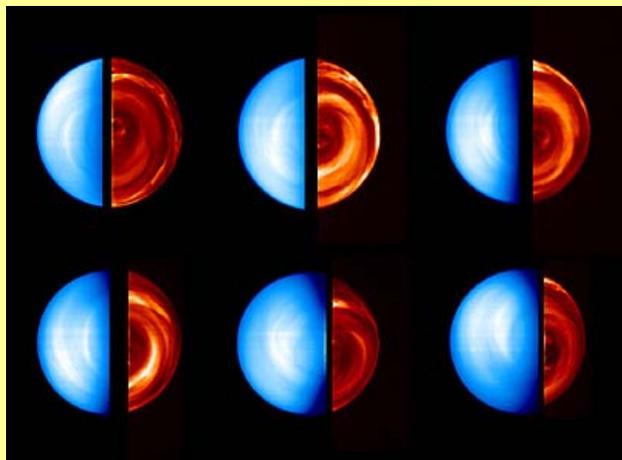
Artist's concept of Venus Express spacecraft operating at Venus since 2006. Courtesy of ESA.

Vignette 5: Venus Express VIRTIS Results

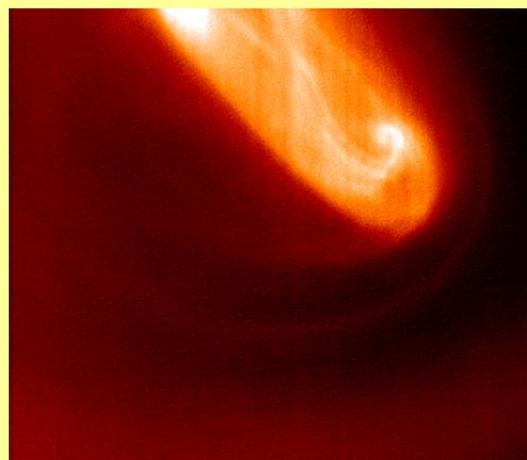
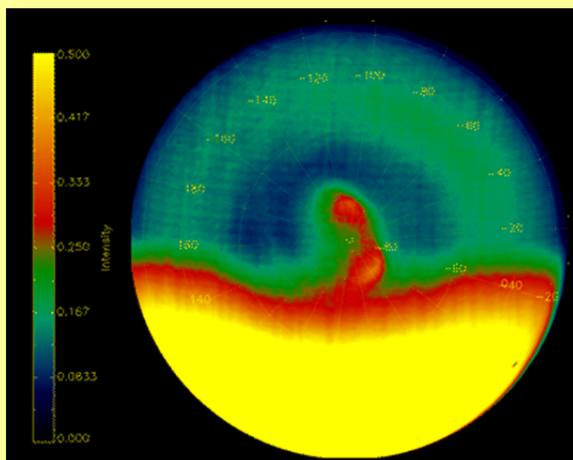


Surface Temperatures. (left) Black-body temperatures measured for the surface correlate well with topography (right), due to decreases of surface temperature with height. Slight variations in this correlation may indicate differences in the surface rock emissivities. Courtesy of ESA.

Vignette 5: 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- μ m 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- μ m 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

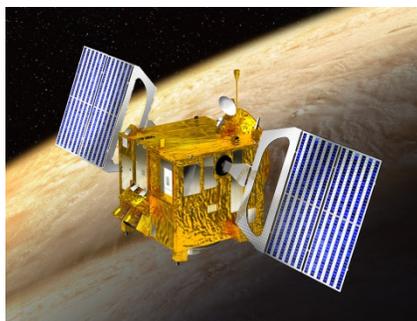
ESA's Venus Express orbiter mission continues to be the only dedicated mission to study Venus at present. The mission has been officially extended through December 2014 by ESA. The spacecraft continues to function well with the project exploring aerobraking operations and new science from a shorter orbit 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 built using space Mars Express spacecraft and instruments. Launched in November 2005, it arrived at Venus in April 2006 and has been continuously sending back science data from its polar orbit around Venus. Equipped with seven science instruments, the main objective of the mission is the long-term observation of the Venusian atmosphere. The observation over such long periods of time has never been done in previous missions to Venus, and is key to better understanding of the atmospheric dynamics. It is hoped that such studies can contribute to an understanding of atmospheric dynamics in general, while also contributing to an understanding of climate change on Earth. Venus Express operations are approved by ESA through 31 December 2014, subject to validation in 2012. Venus Express experiments are:

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

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



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

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 has carrying a suite of instruments for remote sensing in IR, visible, and UV.

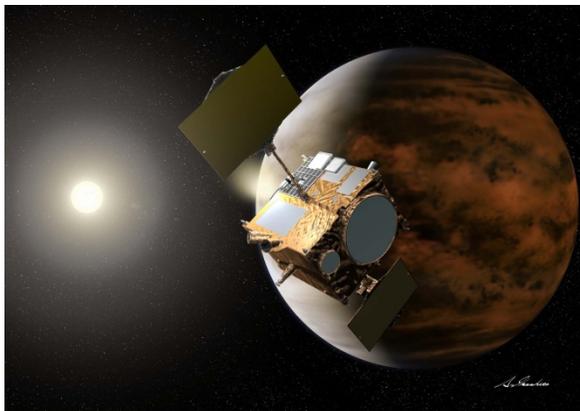
Akatsuki was launched on 21 May 2010 on the H-IIA rocket from Tanegashima Space Center. During a 6.5-month cruise from Earth to Venus, Akatsuki achieved the following: (1) took images of the Earth with 3 on-board cameras (UVI, IR1, and LIR); (2) acquired star-field images including the ecliptic-plane 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. Thus, Akatsuki will encounter Venus again and attempt an orbit insertion in 2016–2018 after 11 revolutions around the Sun.

Akatsuki's instruments are:

- **IR1 and IR2:** IR cameras operating a 1- and 2- μm wavelengths to observe the surface, clouds, cloud particles sizes, and 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:** Lightning 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 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 the station of a 100 kg station on the surface of Venus is limited to 24 hours. Possibility to install seismology, meteorology, and imaging experiments was studied. The data rate may be reached of 10 kbit/s (transmission to orbiter or balloon) or 10bit/s (transmission to the Earth). The sub-satellite utilizes signal from the ground based emitting antenna and recorded by 3 band (L,S,X) 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 Earth-Orbiter and Earth-Subsatellite
2. Ionosphere: 2-band radio occultations
3. Atmosphere: 2 band radio occultations
4. Bistatic radiolocation and near surface atmosphere
5. Surface radiolocation

Scientific goals of this are:

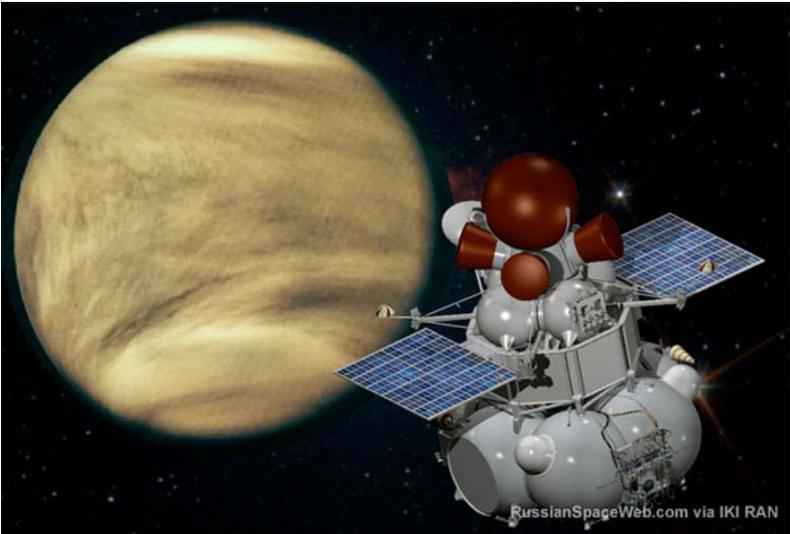
- Investigation of the structure and chemical composition of the atmosphere, including abundances and isotopic ratios of the light and noble gases;
- Thermal structure of the atmosphere, winds, thermal tides and solar locked structures;
- Clouds, structure, composition, microphysics, chemistry;
- Chemical 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, escape rate

Mission Elements are:

- Orbiter (Phobos-Grunt, updated to Venus) in a 24 hour polar orbit, lifetime > 3 years
- Lander (VEGA-type, updated), 2 – 3 hours on the surface
- Long living station, 24 hours on the surface
- Sub-satellite, with 48, 24, 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 interferometeretric spectrometer-interferometer = (1) 5-40 μm ,
 $\nu=(10000)2000-250 \text{ cm}^{-1}$, $\Delta\nu = 1 \text{ cm}^{-1}$
- Solar and star occultation UV spectrometer (0.1-0.3 μm) and IR (2-4 μm)
- MM-sounder $\lambda =3-10$ millimeter
- UV-mapping spectrometer $\lambda = 0.2-0.5\mu\text{m}$, $\Delta \lambda =0.0004 \mu\text{m}$
- IR-mapping spectrometer $\lambda = 0.3-5.2 \mu\text{m}$, $\Delta \lambda= 2.4 \text{ nm}$
- Multispectral monitoring camera
- Radio science (L, S and X ranges)
- Plasma package
- High-resolution heterodyne spectrometer

Sub-Satellite:

- Plasma package
- Radio science

Venera-D Lander Payload

- Active Gamma and Neutron Spectrometric
- Gas chromatography–mass spectrometry (GC-MS)
- Mossbauer spectrometer (MIMOSA-2)
- TV- cameras (landing, stereo, panoramic, high res. up to 0.1 mm)
- MTDLAS – Multi channel tunable diode laser spectrometer
- Nephelometer-particles counter
- Wave-package
- TPW- package
- Optical package
- Radio-science
- Seismometer
- Devices for atmosphere and surface sampling

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 Opportunities

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

4.1. *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.

4.1.1. **Discovery-Class Missions**

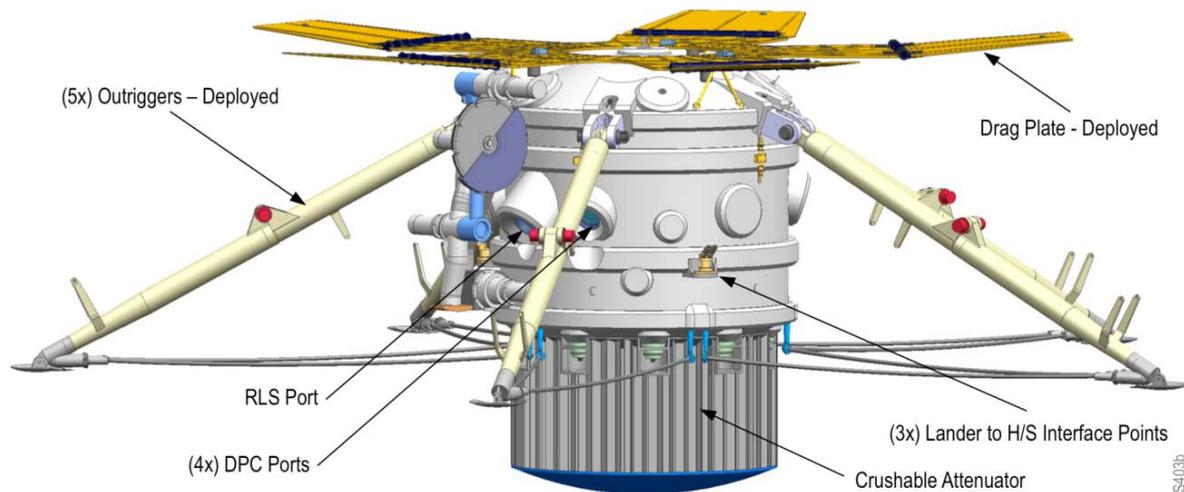
The Discovery Program, which began in the early 1990s, consists of PI-led missions that address targeted investigations with relatively rapid missions. Eleven full missions and five missions of opportunity (instruments and investigations flown on a non-NASA spacecraft as well as extended missions for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

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.

4.1.2. **New Frontiers Missions: Venus In-Situ Explorer (VISE)**

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

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



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

4.2. 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 could 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). Each of these mission concepts is described below.

4.2.1. Venus Climate Mission (VCM)

The Planetary Sciences Decadal Survey [1] recommended a Venus Climate Mission (VCM)—a Flagship mission that 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 (VISE) mission would focus 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, dynamics and chemistry of the Venusian atmosphere. In particular:

- Characterize the strong CO₂ greenhouse atmosphere of Venus.
- Characterize the dynamics and variability of the Venusian super-rotating atmosphere.
- Characterize surface/atmosphere chemical exchange in the lower atmosphere.
- Search for atmospheric evidence of climate change on Venus.
- Determine the origin of the Venusian atmosphere as well as the sources and sinks driving evolution of atmosphere.
- Understand implications of the Venusian climate evolution for the long-term fate of Earth.

To accomplish these objectives, VCM would conduct synergistic observations from an orbiter, a balloon, a mini-probe, and two drop sondes. This would enable the first truly global 3-dimensional (and to a large extent 4-dimensional, via many measurements of temporal changes) characterization of the Venusian atmosphere. The mission would return a dataset on Venus radiation balance, atmospheric motions, cloud physics, and atmospheric chemistry and composition. The relationships and feedbacks among these parameters, such as cloud properties and radiation balance, address the most vexing problems that currently limit the forecasting capability of terrestrial global climate models (GCMs). 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 two drop sondes, mini-probe, and gondola/balloon system to Venus. The carrier spacecraft would provide telecommunications relay once the drop sondes, mini-probe, and gondola/balloon were deployed and then would conduct visible and IR monitoring of the Venusian atmosphere. The drop sondes and mini-probe would measure atmospheric constituents during a 45-minute descent from 55 km to the surface. The gondola/balloon system would conduct a 21-day atmosphere-monitoring campaign at 55 km. Instrumentation would be:

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

4.2.2. Venus Intrepid Tessera Lander (VITaL)

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

4.2.3. Venus Mobile Explorer (VME)

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

4.2.4. Venus Flagship Design Reference Mission (VFDRM)

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 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.

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

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

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

These questions translate to three major themes:

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

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

and their payloads would be designed to operate for 1 month at an altitude of 55 km, circumnavigating the planet several times, while gradually drifting from mid-latitudes towards the polar vortex.

VFDRM 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.

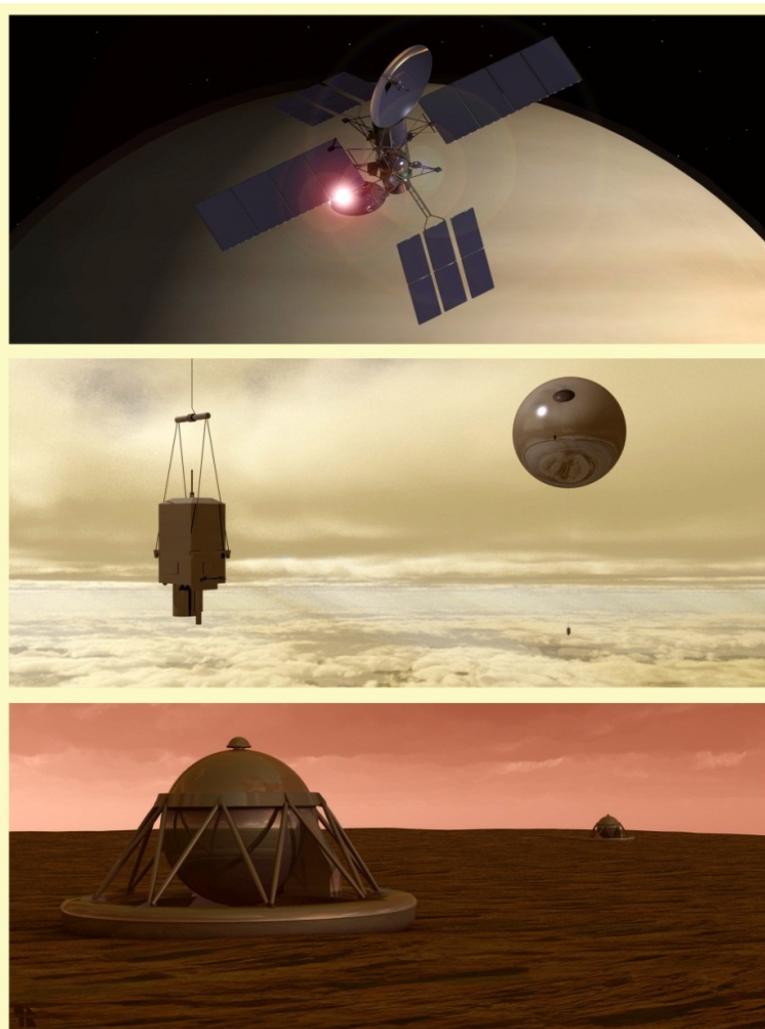


Figure 4-1. Artist's concept of Venus flagship orbiter, balloons, and landers—elements of the Venus Flagship Design Reference Mission, developed by the Venus STDT in 2008–2009. Artwork by Tibor Balint.

5. Venus Laboratory Measurements

5.1. Laboratory Measurements of Venus System Variables and Processes

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

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

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

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

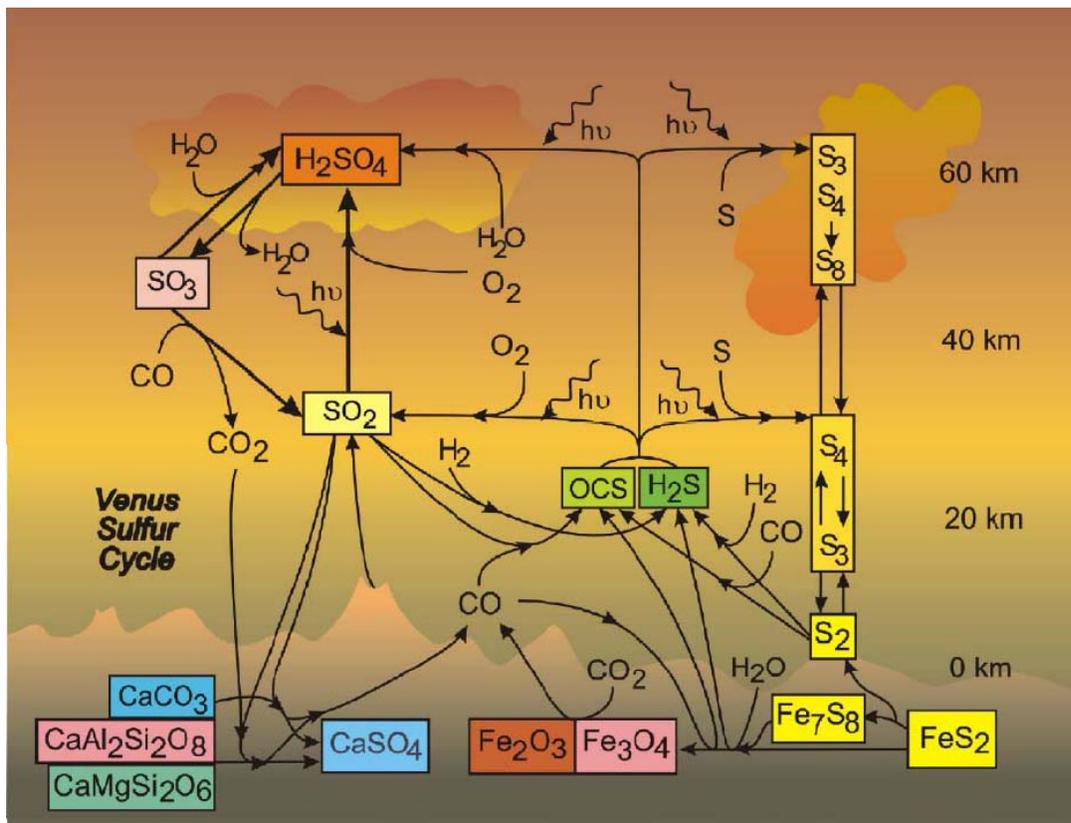
Context	Category 1 Measurements of Venus System Variables	Category 2 Measurements of Venus System Processes
	Near-surface atmospheric sounding: cm wavelength properties of CO ₂ and OCS >30 bars	
	Supercritical CO ₂ in new temperature range at high pressures	
Surface	Chemical weathering of surface materials (basalts): reaction rates, decomposition rates	Scattering properties
	Spectroscopic (visible, near-IR) characteristics of various ferric/ferrous, silicate, sulfate, and hydroxide under Venus conditions	
	Surface conductivity sounding: dielectric loss properties at 750 K for various basalts and other major rock types	
	Atmospheric IR opacity: Very high-pressure, high-temperature CO ₂ and H ₂ O spectroscopy, isotopologues, O ₃ , O ₂ , H ₂ , etc.	
	Fundamental thermophysical data: specific heat, speed of sound, equation of state, thermal expansion coefficients	
Technical issues	Stability of spacecraft materials, and rates of reaction/corrosion with hot supercritical CO ₂ -SO ₂ gas	
	Chemical transfer of elements from surface into atmosphere (and onto spacecraft windows?)	

A Venus Environmental Test Facility would enable:

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

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

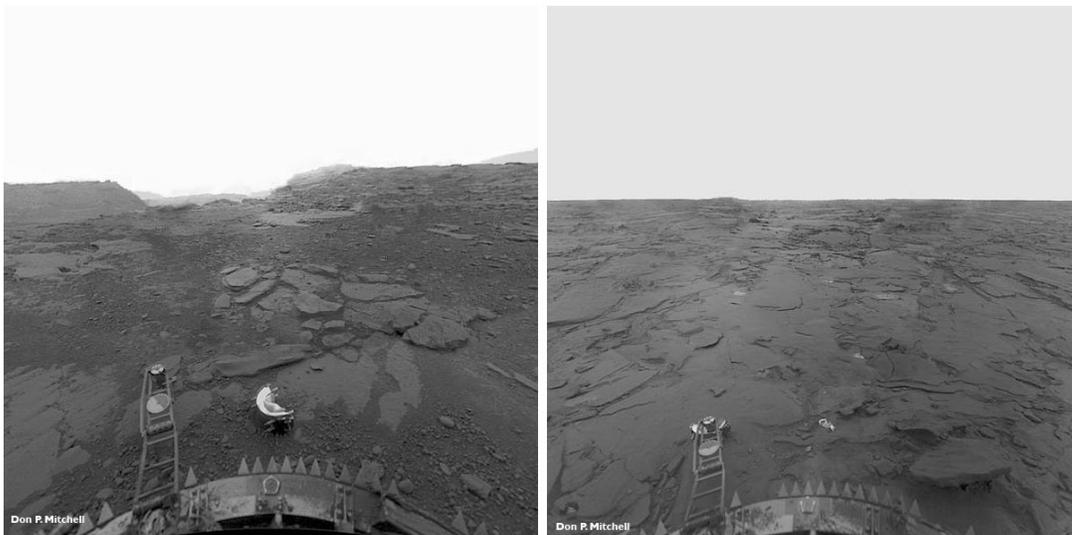
Facilities for laboratory investigations at extreme Venusian temperature and pressure conditions can be small and devoted to particular investigations. Larger chambers for spacecraft and instrument testing under Venusian conditions would enable the general scientific community to perform laboratory investigations.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



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

5.2. Venus Environmental Test Facility Capability List

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 to 103	20 to 500	CO ₂ , N ₂ , H ₂ O, 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 ₂ O, 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 ₂ O, 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. Acronyms and Abbreviations

AO	Announcement of Opportunity
ASPERA	Venus Express fields and particles experiment/ Analyser of Space Plasmas and Energetic Atoms.
CCD	charge-coupled device
ESA	European Space Agency
GSFC	NASA Goddard Space Flight Center
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
IR1 and IR2	Akatsuki's infrared cameras
JAXA	Japanese Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LAC	Akatsuki's Lightning and Airglow Camera
LANL	Los Alamos National Laboratory
LIR	Akatsuki's long wavelength infrared camera
MAG	Venus Express magnetometer experiment
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NRC	National Research Council
PI	Principal Investigator
PLANET-C	Akatsuki (Japan's Venus Climate Orbiter)
RS	Akatsuki's Radio Science experiment
SAGE	Surface and Geochemistry Explorer, New Frontiers Venus In-Situ Mission
SPICAV–SOIR	Venus Express infrared and ultraviolet imaging spectrometer
STDT	Science and Technology Definition Team
US	United States
UV	ultraviolet
UVI	Akatsuki's ultraviolet imager
VCM	Venus Climate Mission
VCO	Venus Climate Orbiter (Planet-C, Japan's Akatsuki Mission)
Vega	Russian Halley/Venus Lander and Orbiter Mission
VeRa	Venus Express radio science experiment

VEXAG	Venus Exploration Analysis Group
VFDRM	Venus Flagship Design Reference Mission
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer (Venus Express)
VeRa	Venus Radio Science Experiment (Venus Express)
WISE	Venus In Situ Explorer
VITaL	Venus Intrepid Tessera Lander
VMC	Venus Monitoring Camera (Venus Express)
VME	Venus Mobile Explorer



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

APPENDIX A. WHY EXPLORE VENUS NOW?

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

Sanjay S. Limaye, VEXAG Chair, 04 November 2011

Introduction

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

Time and again, studying Venus has resulted in revolutionary changes to our thinking about Earth. The first glimpse of the depths of Venus by the very first interplanetary spacecraft, Mariner 2 in 1962, revealed an unexpectedly hot atmosphere 200 K warmer than predicted, thus revealing the importance of the greenhouse effect in determining planetary climates. As well, the

role of CFC (chlorofluorocarbons) in ozone chemistry - so important in explaining the ozone hole in the Earth's southern polar atmosphere - was discovered by Venus scientists to explain the chemistry of chlorine and other trace molecules in Venus' upper atmosphere. The recent discovery of an ozone layer (and other species) in Venus' atmosphere by the European Space Agency's (ESA's) Venus Express orbiter provides an opportunity for comparative atmospheric studies. As another example, a widely accepted mechanism for the demise of the dinosaurs on Earth was the development of a decade-long, globe-girdling Venusian-style sulfuric acid cloud layer resulting from the impact of a bolide in the Yucatan peninsula some 65 million years ago, which resulted in a dramatic cooling at the Earth's surface. The enhanced CO₂ content due to extensive fires generated by the impact then warmed the planet to historically high temperatures. Both of these severe climatic results of the dinosaur-killing impact stemmed directly from Venus studies.

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

Background

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

“In the 1960s and 1970s, observations of Mars and Venus showed that planets that seemed much like the Earth could have frightfully different atmospheres. The greenhouse effect had made Venus a furnace, while lack of atmosphere had locked Mars in a deep freeze. This was visible evidence that climate can be delicately balanced, so that a planet's atmosphere could flip from a livable state to a deadly one.”

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

Further, he writes:

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

conclusions about climate. The project was mostly canceled in 1952” (Doel, 1966).

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

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

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

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

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

- (1) To determine, more completely, the vertical and horizontal distributions of radiative heating and cooling, and the relationship of radiation fluxes to clouds,
- (2) To define the mean atmospheric state, including the large-scale wind distribution,
- (3) To define smaller scale and transient wind systems, and identify their mechanisms,
- (4) To discover whether clues to past atmospheric processes are imprinted in the surface

The observations recommended were:

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

The report further concluded:

“In addition to the opportunity to test the generality of physical parameterizations derived from terrestrial experience, under vastly different conditions, planetary science has already provided a number of examples in which the experience and skills developed in the study of other planets have accelerated progress in understanding of terrestrial problems. Speed in narrowing the uncertainties surrounding estimates of various earth climatic theories has become a clear need in view of such possible human influences on climate as the potential for alteration of the ozone layer or of changing the heat balance by increasing the CO₂ concentration. Research in both problem areas has already benefited from the existence of a planetary research program. For example, the study of the radiative properties of CO₂ for the conditions on Venus led to a parameterization of the CO₂ influence on radiation. Although originally intended for Venus application, this parameterization has subsequently been widely used for calculations in the earth’s stratosphere. Undoubtedly, such a development would eventually have occurred for earth, but the existence of a scientific effort in planetary atmospheres speeded up the process considerably. In fact, much of radiative transfer theory now in common usage in earth applications was originally developed for extraterrestrial applications.”

As another example, one component of some earth climatic theories is the parameterization of horizontal and vertical heat fluxes as functions of the large-scale thermal forcing. Some of these theories, which are at the core of highly parameterized earth climate models, were originally developed in the

context of comparative planetary studies. The point is not that such parameterizations are necessarily “correct,” or even “optimal,” but they have generated controversy and have stimulated others to explore this problem...”

The report summarized its findings by identifying two items:

- (1) Simulation models and mechanistic models can be applied to other planets as well as to the Earth. If the actual circulations of the planetary atmospheres are known, this application provides a means of testing model performance under very different conditions. In so doing, this helps to validate use of the models to examine climate, when the external conditions governing climate are very different from those of the present.
- (2) Many physical processes which occur in the Earth’s atmosphere also occur in the atmospheres of other planets, but in a more extreme form. The study of planetary atmospheres helps us to gain a better fundamental understanding of such processes, and perhaps even to identify terrestrial processes which would otherwise be missed.

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

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

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

Sample Mission Concepts for a Better Understanding of Venus

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

- The Noble gas and Trace Gas Explorer is the highest priority mission because its data are vital to our understanding of the origin of Venus. This small mission requires a single entry probe that will carry the state-of-the-art instruments needed to complete the noble gas inventories between the cloud tops and the surface.
- The Global Geological Process Mapping Orbiter is a small to medium class mission. It will carry a C-band (13 cm) and/or X-band (4 cm) radar designed for stereo or interferometric imaging, to provide global maps of the surface at horizontal resolutions of 25 to 50 meters. These data are needed to identify and characterize the geological processes that have shaped the Venus surface.
- The Atmospheric Composition Orbiter is a small mission that will carry remote sensing instruments for characterizing spatial and temporal variations in the clouds and trace gases throughout the atmosphere. This mission will collect the data needed to characterize the radiative, chemical, and dynamical processes that are maintaining the thermal structure and composition of the present atmosphere.
- The Atmospheric Dynamics Explorer is a small to medium mission that will deploy 12 to 24 long-lived balloons over a range of latitudes and levels of the Venus atmosphere to identify the mechanisms responsible for maintaining the atmospheric superrotation.
- The Surface and Interior Explore is a large mission that will deploy three or more long-lived landers on the Venus surface. Each lander will carry a seismometer for studies of the interior structure, as well as in-situ instruments for characterizing the surface mineralogy and elemental composition. This mission requires significant technology development.

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

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

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

In the meantime, NASA also undertook a study of a flagship mission to Venus (Bullock et al., 2009), just prior to the 2011 Decadal Survey of Planetary Science. A scaled down version of this mission was recommended by this survey (Venus Climate Orbiter). The Mars Express spare was sent to Venus by ESA in November 2005 to become the Venus Express orbiter, and the Japanese Space Agency (JAXA) launched Akatsuki/Venus Climate Orbiter in May 2010 which is now awaiting a second attempt at orbit insertion around Venus in 2015, having missed it the first time in December 2010. These and other missions proposed to Discovery Program remain hopes and dreams to obtain important new observations, but the time for NASA to explore Venus is now.

Modeling the Climate of Venus

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

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

especially true as substantial increases in the carbon dioxide and water vapor are considered for Earth.

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

In the last few decades the discovery of life in extreme environments has led to a new concept of the habitable zone. As we look for life elsewhere, it is also important to remember that the Venus clouds present a potentially habitable environment for certain bacteria (Sagan, 1971; Schulze-Makuch and Irwin, 2002; Schulze-Makuch et al., 2004). Although they commonly originate from the surface, bacteria have been found at high altitudes, including in cosmic dust samples (Yang et al., 2009); hence it would be worth testing the habitability of the Venus clouds. An experiment to make such observations was described at the 9th VEXAG meeting (Juanes-Vallejo, 2011).

Sun-Climate Connection on Venus and Earth

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

The data gap that hampered the effort in the late 1940’s to simulate other atmospheres has now been significantly reduced, but not eliminated for Venus through the last few decades of spacecraft data from US, Soviet and European missions to Venus. Besides lending balance to the

Planetary Science Division, exploration of Venus holds implications for extrasolar planets, the sun-Earth connection and habitability--all of topics of interest to the Earth Science, Heliophysics, and Astrophysics Divisions of NASA/SMD. An effort comparative climatology of terrestrial planets by NASA/SMD is thus highly desirable.

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

Summary

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

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

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

Efforts focusing on the evolution of Venus will help us understand not only the evolution of Earth but terrestrial planets around other stars as well. Since exoplanets are being discovered ever more rapidly, it is even more important to understand Venus and its evolution in order to interpret the more detailed data that will be obtained on exoplanets in the near future. This is in addition to the urgency in understanding planetary atmospheres well enough to save our own.

Venus marks the inner boundary of the habitable zone in our solar system. As most of humanity would agree, it should be at least as important to learn about the Earth's future as its past.

In summary, Venus exploration now is crucial to:

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

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

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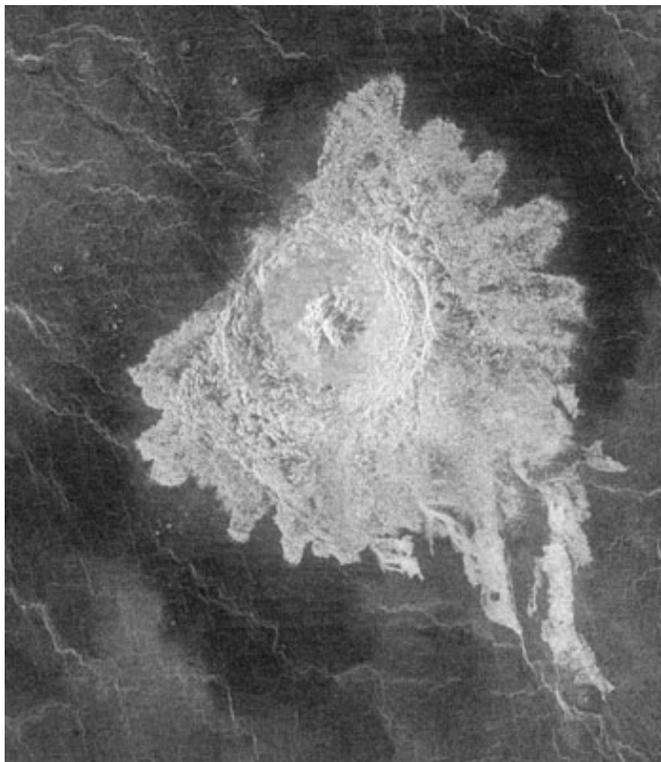
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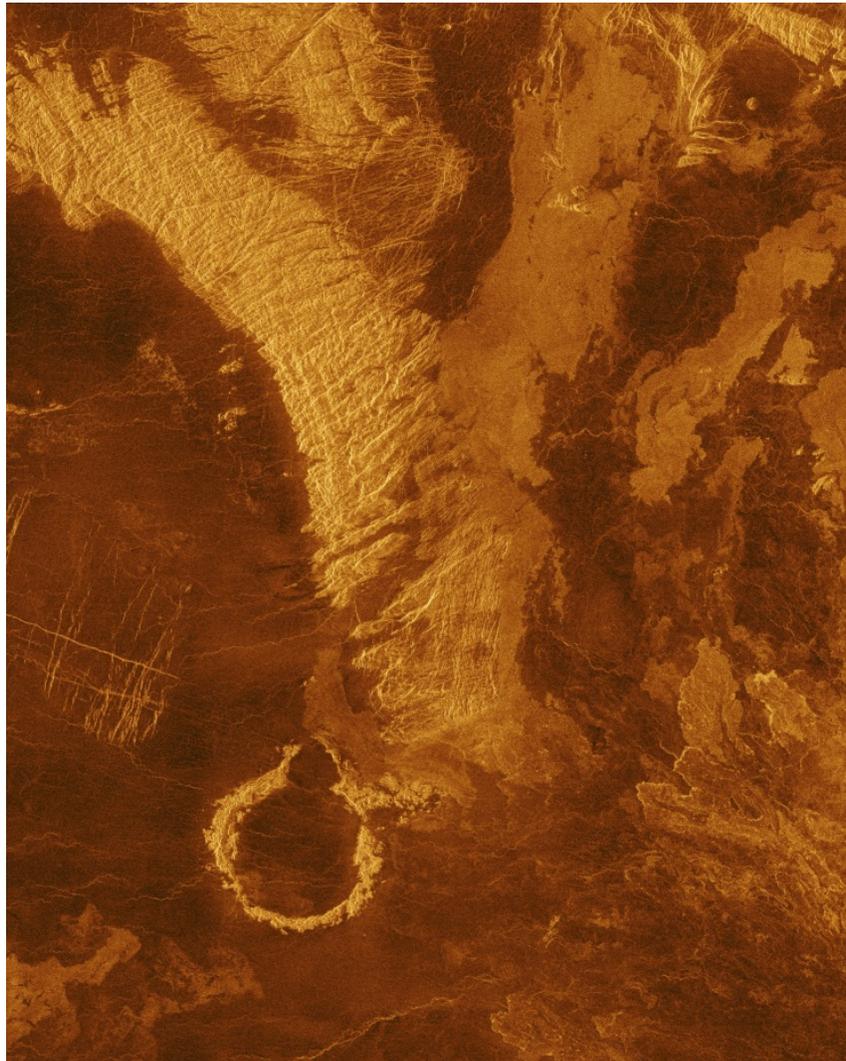
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Venus impact crater Aurelia, about 20 miles across, is surrounded by a thick blanket of ejected material. A small "tail" of melted rock flowed away from the crater to the lower right. Courtesy of NASA/JPL-Caltech



Magellan Image of Leda Planitia

This false-color Magellan image shows a 220-by-275 kilometer portion of Leda Planitia centered at 41 degrees North latitude, 52 degrees East longitude. This image shows the major geologic terrains on Venus and illustrates the basic stratigraphy of Venusian geologic events. The oldest terrains (in the upper left) are the tessera that appears as bright, highly-fractured chaotic highlands rising out of the plains. The tessera, which is older and forms a thicker crustal material, occupy 15 percent of the Venusian surface. The circular ring structure in the lower left of the image is a 40-kilometer diameter impact crater that was formed before or when the plains lavas embayed and covered this region. The most recent volcanic activity appears as the radar-bright flows in the upper right quadrant of this image. Those flows are similar to the radar-darker plains lavas, but have more rugged surfaces and thus more efficiently scatter the radar signals back to the spacecraft. The simulated hues are based on color images recorded by the Soviet Venera 13 and 14 spacecraft. Courtesy of NASA/JPL-Caltech.