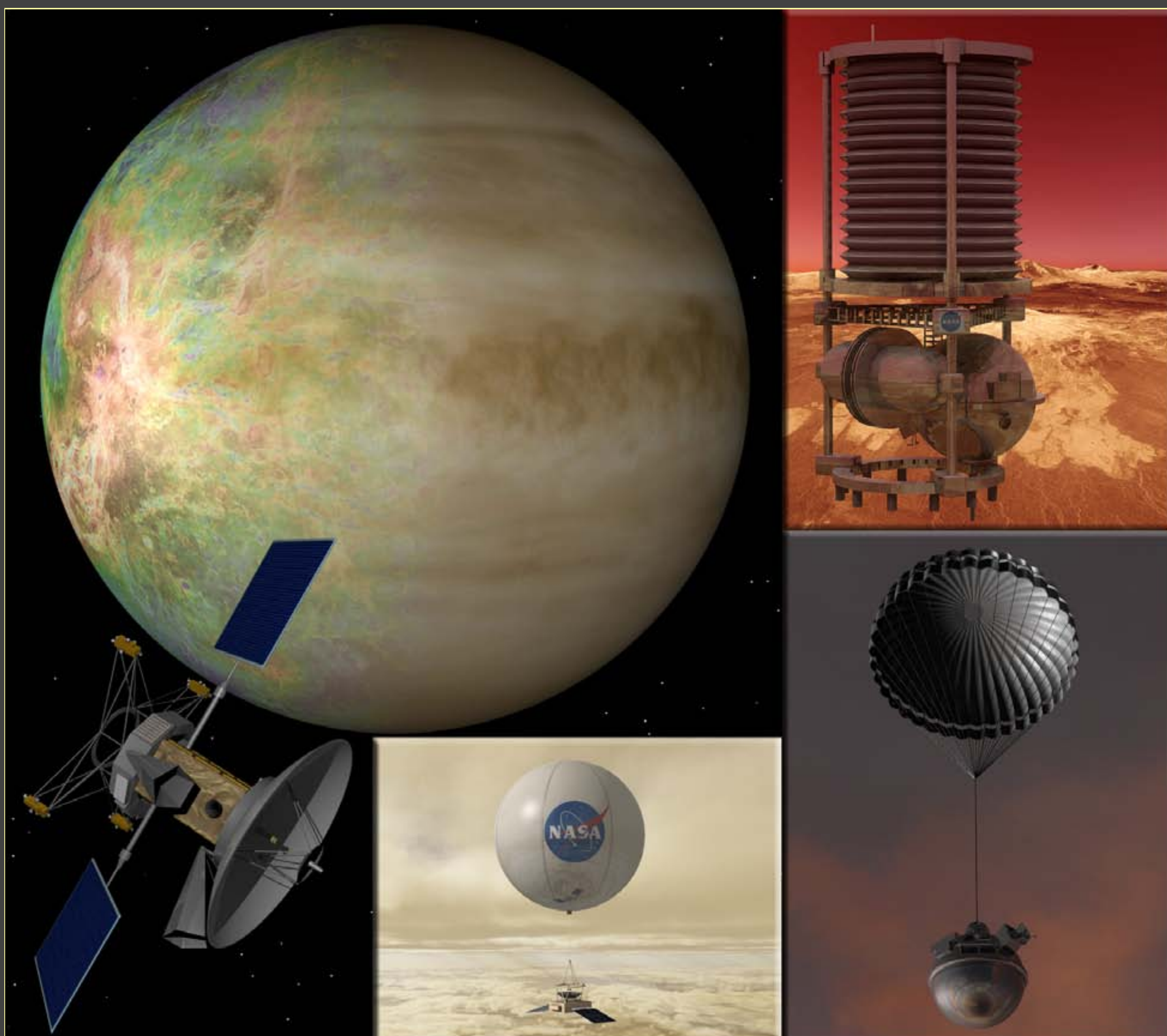
Venus Exploration Goals, Objectives, Investigations, and Priorities: 2007

A Report of the Venus Exploration Analysis Group (VEXAG)

October 2007



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

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

Front cover is a collage showing Venus at optical wavelength, the Magellan spacecraft, and artists' concepts for a Venus Balloon, the Venus In-Situ Explorer, and the Venus Mobile Explorer.

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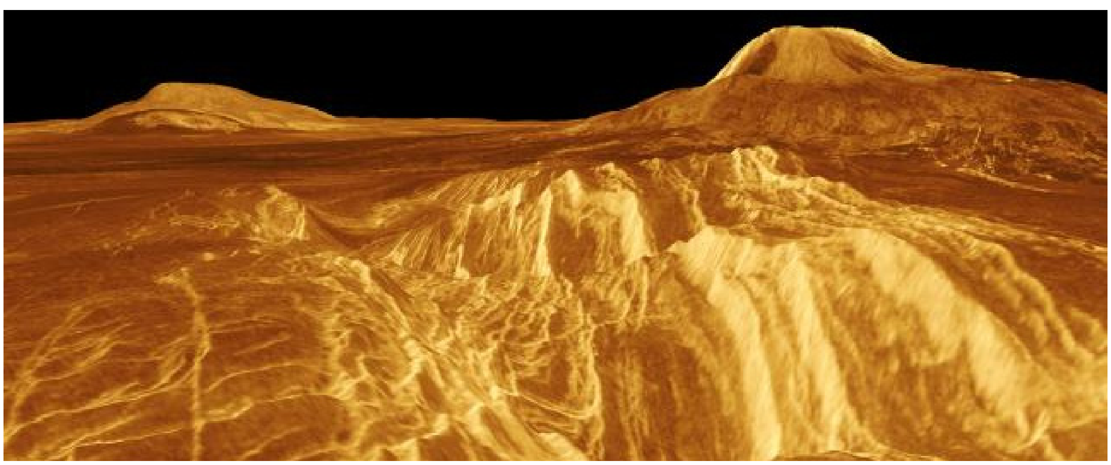
VEXAG Charter

VEXAG is a community-based forum designed to provide science and technology development input for planning and prioritizing Venus exploration activities for the next several decades. It is chartered by NASA's Planetary Science Division at NASA HQ, and reports its findings at the Federal Advisory Committee Act (FACA)-sanctioned meetings of the Planetary Science Sub-Committee of the Science Committee of the NASA Advisory Council. Open to all interested scientists, VEXAG regularly comments on Venus exploration goals, objectives, investigations, and required measurements on the basis of the widest possible community outreach. NASA's JPL has been directed to manage the logistics associated with the operations of VEXAG on behalf of NASA's Planetary Science Division.



Magellan panorama showing tectonic faulting in the foreground and volcanic edifices in the background.

EXECUTIVE SUMMARY

As discussed in Sections 1 and 2 of this document, previous and current missions to Venus, our nearest planetary neighbor in the solar system, raise fundamental un-answered scientific questions about Venus. These questions are:

- Was there ever an ocean on Venus, and if so, when did it exist and how did it disappear?
- Was the early Venus atmosphere like the early atmosphere of Earth, and at what point did it diverge in character so greatly and why?
- Why does Venus rotate so slowly and is the lack of a planetary dynamo a consequence? What was the impact on the evolution of Venus?
- Why does Venus' atmosphere rotate 60-times faster than its solid body? How are atmospheric heat and momentum transferred from equator to poles?
- What caused the extensive resurfacing of Venus during the last billion years? Is Venus still an active planet? Are the resurfacing and climate change related?
- Was Venus ever habitable?

As the closest counterpart to Earth in size, initial composition and solar-radiative influences, scientific understanding of the evolution of Venus will yield unmatched insights into the past history and future of Earth. However, study of Venus has challenging hurdles, including its cloud cover that obscures the surface from conventional remote sensing and its inhospitable lower atmosphere and surface environment that challenge robotic in-situ exploration. Venus science is currently experiencing a renaissance with the advent of the European Space Agency's (ESA) Venus Express spacecraft presently in orbit around Venus, the Japanese Aerospace Exploration Agency's (JAXA) upcoming Venus Climate Orbiter, and the June 2007 flyby of Venus by the MESSENGER spacecraft on its way to Mercury. In addition, current knowledge of the outstanding questions for Venus research are documented in an AGU monograph and JGR special issue, which summarizes the proceedings of a well-attended Chapman Conference on Venus held in February 2006.

In parallel with these developments, NASA Headquarters in July 2005 formed VEXAG (Venus Exploration Analysis Group) to provide a forum for community discussions of future Venus exploration. VEXAG, like the Mars, lunar and outer planet analysis groups, is open to all interested scientists and engineers, and tasked by NASA to consider priorities for advancing Venus science through future mission and research activities. VEXAG through its interactions with the community, developed a set of three overarching scientific goals:

- ***Origin and Early Evolution of Venus: How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and conditions of habitable environments on Venus and similar extrasolar systems?***
- ***Venus as a Terrestrial Planet: What are the processes that have shaped and still shape the planet?***
- ***Implications for Earth: What does Venus tell us about the fate of Earth's environment?***

The objectives and investigations to accomplish these goals have been identified and are presented here in Section 2. The technologies and missions architectures to accomplish these goals are discussed in Sections 3 and 4.

Recommendations for Venus missions have come from a number of previous study groups. A Venus In-Situ Explorer (VISE) was listed as a possible mission among those solicited in the last announcement of opportunity (AO) for New Frontiers (NF) missions, and is still under consideration for the next New Frontiers AO, subject to the current National Research Council (NRC) review of the process for identifying NF mission candidates. The science goals for a VISE mission were described in the last NRC Solar System Exploration Decadal Survey* as well as in the recent (2006) NASA Solar System Exploration Roadmap**. The goals for VISE were reviewed by VEXAG and found to be still important and valid. However, a mechanism for efficient, relevant technology development to reduce risk for Venus missions, even in the New Frontiers class needs to be identified. These developments are critical to enabling a subsequent, more ambitious Flagship class mission such as a Venus Mobile Explorer (VME) mission, also noted in the Solar System Exploration Roadmap. In parallel, a technology development program is needed to align technology developments with potential missions and establish performance goals (as described in the Technology Development Finding and Proposed Action below).

As discussed in Section 5, The VEXAG discussions and deliberations to date, together with the priorities documented here, lead to the following overall findings and proposed actions addressing the next steps toward Venus exploration.

Venus Science

> ***Finding:*** Without additional resources, the U.S. Venus science community will fall further behind in Venus exploration leadership. There will be no opportunity to fully take advantage of the results of either the Venus Express mission or the MESSENGER flyby in our future plans for Venus exploration, or to train the next generation of Venus scientists.
>
> ***Proposed Action:*** In order to fully exploit the results from both the Venus Express and MESSENGER at Venus, made available via the Planetary Data System, funds should be identified to amend the NASA Research Announcement to include a Venus Data Analysis Program open to all.

Venus Flagship Mission

> ***Finding:*** The completion by VEXAG of scientific goals and priorities now makes it timely to initiate a study of a Venus Flagship mission to define a concept in more detail and identify the technologies needed to implement the mission. This study should not be delayed because a path to addressing specific-technology challenges that the resulting mission-concept raises must be embarked upon at the earliest opportunity.

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* NRC Decadal Survey for Solar System Exploration (2003): http://www.nap.edu/catalog.php?record_id=10432#toc

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

Proposed Action: NASA should initiate a study of a Flagship mission to Venus at the earliest opportunity**.** The study should assess:

- Key scientific questions that can be addressed by a long-duration mobile mission to the surface or near-surface of Venus.
- Alternative-mission architectures for addressing these scientific questions.
- Precursor-scientific measurements and technology validation that might be implemented with prior Discovery and New Frontiers missions.
- Technology investments needed to enable the Venus Flagship mission emphasizing - long-lead time technologies needing early investment.

Venus New Frontiers Mission

Finding: VEXAG considers that the Venus In-Situ Explorer continues to be a vital mission to explore Venus and should be included in the FY08 New Frontiers AO. The scientific goals stipulated in the FY03 NF AO remain valid. In addition to its scientific value, the VISE mission offers a unique opportunity to validate capabilities that would be important to a future Flagship mission.

Proposed Action: The Venus In-Situ Explorer should be included in the New Frontiers AO for 2008 and the general scientific goals for this mission should remain unchanged. NASA should consider implementing a technology-validation element for VISE in particular that would permit demonstration of technologies needed for a long-duration mobile mission but not necessary to the success of VISE itself.

Technology Investments

Findings: There are credible-technical approaches, leveraging from technologies developed in industry to achieving extended operation in the Venus environment. High-temperature electronics can enable systems to operate for extended periods in the corrosive, high-pressure on Venus' surface. Advanced radioisotope-power systems and active thermal-control systems could enable conventional components such as microprocessors or imaging sensors to operate for extended periods on Venus' surface. While further work on mission architectures will be needed to define specific performance goals and the technology focus, technology work can and should begin now. Without NASA's direct involvement, it will not be possible to apply the results from industry to the specific needs of in-situ and near-surface exploration.

Proposed Action: NASA should initiate a program to develop technologies for operation in Venus' extreme environment. These should include:

- Passive thermal-control technologies for extending operation on or near the surface from hours to days.
- Active thermal-control technologies and power-generation systems for extending Venus operations to many months.
- High-temperature electronics and other components capable of extended operation directly exposed to the Venus surface environment.

- Mobility systems for operation at the surface and in the lower atmosphere of Venus.
- A program of systems analyses to establish performance objectives and evaluate alternative approaches for mission architectures.

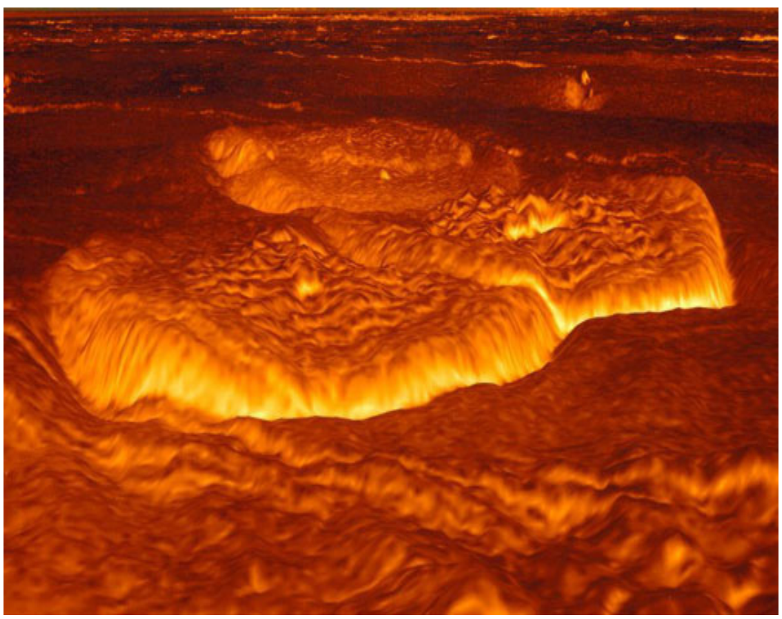
If funds were available, this could be competed through an amendment to the ROSES NRA, perhaps as part of a larger extreme-environments technologies initiative.

Venus as a Future Earth

Finding: A useful dialogue between Venus and Earth scientists is lacking.

Proposed Action: A research program, encouraging conferences and/or workshops, should be initiated that brings together Earth scientists and Venus scientists for a focused study of the evolutionary aspects (past and future) of these terrestrial-planet twins. Areas of mutual interest could include extreme climate scenarios, and/or the role of volcanism, tectonics, and the presence/absence of a planetary dynamo in determining the fate of a planet and its atmosphere.

In summary, VEXAG strongly suggests that these proposed actions be enacted immediately. Furthermore, VEXAG strongly endorses progress toward the definition of Flagship mission concepts under a separately appointed NASA Science Definition Team (SDT) to be formed in the coming year.



Magellan panorama showing the enigmatic pancake volcanoes.

1. INTRODUCTION

1.1 Venus: Earth's Past and Future Twin?

Venus represents a unique realization of a terrestrial planet - as distinct from the Earth, Mars and Mercury as Titan and Io are from the other Galilean and Saturian satellites. Reasons for the divergent nature of these orbiting bodies are as varied as the bodies themselves. However, Venus is particularly compelling because it is so like Earth in size, and orbits only slightly closer to the Sun as a mere 0.3 AU separates Venus from Earth in a solar system which is >30 AU in scale. Although called "Earth's twin," it is a far cry from it in terms of surface habitability. Thus, Venus can provide valuable insights into our origins, and our ongoing searches for terrestrial planets in our galaxy. Although Mars may provide a more hospitable environment for humans and life, Venus provides insights into possible states of terrestrial planets, as well as Earth's future evolution.

In 2003, Crisp and co-authors [1], as part of a science-community contribution to the first National Research Council Solar System Decadal Survey [2], summarized what has been learned from previous missions to Venus, including the Soviet Venera Lander and Vega balloon missions, the more recent Pioneer Venus Orbiter and Probe, and Magellan radar missions, and the current and near-future Venus Express and Venus Climate Orbiter missions. (These missions and their obtained or anticipated results are described in the vignettes that follow in this chapter.) Crisp and co-authors suggested the following scientific themes and the key knowledge areas for future research and exploration of Venus:

- *Past: Origin of terrestrial planets in our solar system*
    - Noble and trace gases as evidence of early history and evolution
    - Surface properties and age determination
    - The history of interior volatiles
- *Present: What processes shape the terrestrial planets?*
    - The Venus greenhouse mechanism
    - Atmospheric super-rotation
    - Lightning
    - Middle-atmosphere composition and dynamics
    - Thermospheric composition and dynamics
    - Ionospheric structure, composition and dynamics
- *Future: What does Venus tell us about the fate of the Earth's environment?*
    - Venus runaway greenhouse and the future of the Earth
    - The limits of plate tectonics and future geologic processes on Earth

Measurements to address these key knowledge areas include:

- High-resolution imaging of the surface and radar probing of the subsurface,
- Surface mineralogical and chemical weathering investigations,
- Seismicity, heat flow, and other probing of the interior,
- Abundances of noble gases and their isotopes,
- Trace gas and volatile composition and abundances from the upper atmosphere to the surface, with wide-ranging spatial and temporal sampling,
- Detection of radiation fields within the atmosphere and on the surface,
- In-situ and remote imaging of the cloud layers and their dynamics (including winds) and variability,
- Lightning detection by electromagnetic and/or optical means,
- Atmospheric composition, density, temperature and dynamics measurements from the surface through the thermosphere, including the ionosphere, and
- Ionospheric and exospheric observations pertaining to atmosphere escape, and the contextual information to interpret them.

Previous and current missions have provided insights into what should be addressed next. Some measurements are achievable with currently available technologies, while others require ambitious technological advances (such as the technologies for landed or long-term atmospheric in-situ instrumentation).

Crisp and co-authors and the NRC Solar System Decadal Survey concluded that further research and analysis of existing Venus data are needed to understand how Venus operates as a system and how it arrived at its present state. A renewed program focusing on Venus was called for as an important target for NASA scientific exploration. Several Venus missions in all size ranges were suggested in order to address the key questions in a systematic and reasonable way. These suggested missions included a small noble and trace gas explorer, a small-to-medium class global geological-process mapper, a small atmospheric-composition orbiter, a medium atmospheric-dynamics explorer with an orbiter and balloons, a large class surface and interior explorer mission including a small network of landers, and finally a major sample-return mission.

A new 2006 Solar System Roadmap [3] investigated Venus missions with goals that mirror those in the Crisp (2002) paper [1] and NRC Decadal Study [2]. Although Discovery Class missions are left undefined, this Solar System Roadmap included a New Frontiers Venus mission to perform in-situ sampling and analysis of the atmosphere and surface, as well as a subsequent sample-return flagship mission. This mission sequence has surface and lower atmosphere remote sensing and upper atmosphere in-situ measurements from orbit, followed by a visit to the surface including first measurements and sampling technology demonstrations, which in turn is followed by sample return.

A Chapman Conference on Venus as a terrestrial planet was held in February 2006 [4, 5]. At that conference the concept that Venus had an ocean and a relatively mild climate for the first few billion years of its history was presented, and prompted a revised focus for future research, whereby our goal for Venus includes the search for fossil biosignatures, and the existence of a past ocean.

1.2 The Role of VEXAG

NASA's Science Mission Directorate established the Venus Exploration Analysis Group (VEXAG) in July 2005 in order to identify scientific priorities and strategies for the exploration of Venus. VEXAG supports NASA with a community-based forum that provides scientific input and technology-development requirements for planning and prioritizing Venus exploration. VEXAG will report its findings and provide input to NASA, but will not make recommendations.

VEXAG is currently composed of two co-chairs, Drs. Sushil Atreya and Janet Luhmann, and three focus groups: Planetary Formation and Evolution: Surface and Interior, Volcanism, Geodynamics, etc, led by Dr. Stephen Mackwell; Atmospheric Evolution: Dynamics/ Meteorology, Chemistry, Solar Wind Interaction, Escape, etc., led by Dr. Kevin Baines; and Technology for Venus in-situ Exploration, led by Dr. Jim Cutts. Each focus group includes technology experts, NASA representatives, international partner representatives, EPO experts, and the two VEXAG co-chairs. Other focus groups may be constituted, as needed.

This document, *VEXAG Goals, Objectives, Investigations, and Priorities*, has been developed as a means to coordinate and disseminate information on the high-priority community desires for Venus exploration. It is intended that this document remain a living document with revisions on an as needed basis to capture the consensus community views of the Venus-scientific community.

1.3 Background: Other Recent Reports Addressing Venus Exploration

As mentioned earlier, several major studies involving Venus exploration have been carried out in the last five years by the National Research Council (NRC) and by NASA. These studies included the NRC Decadal Survey for Solar System Exploration (2003) [2], with the companion paper by Crisp [1], the NASA Science Plan (2006) [6], and the NASA Solar System Exploration Roadmap (2006) [3]. As the results of these studies provide the foundation for the present expectations for Venus exploration, their findings on Venus science and missions are summarized here.

a. New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)—The NRC Decadal Survey for Solar System Exploration

The most relevant section of the Solar System Decadal Survey for Venus exploration is Chapter 2, "Inner Solar System: Key to Habitable Worlds". Unifying themes for studies of the inner planets identified in this report were:

- The past: Where did we come from? What led to the uniqueness of our home planet?,
- The present: What is going on? What common-dynamic processes shape Earth-like planets?, and
- The future: Where are we going? What fate awaits Earth's environment and that of the other terrestrial planets?

Vignette 1: Lessons Learned from Pioneer Venus Orbiter and Huygens

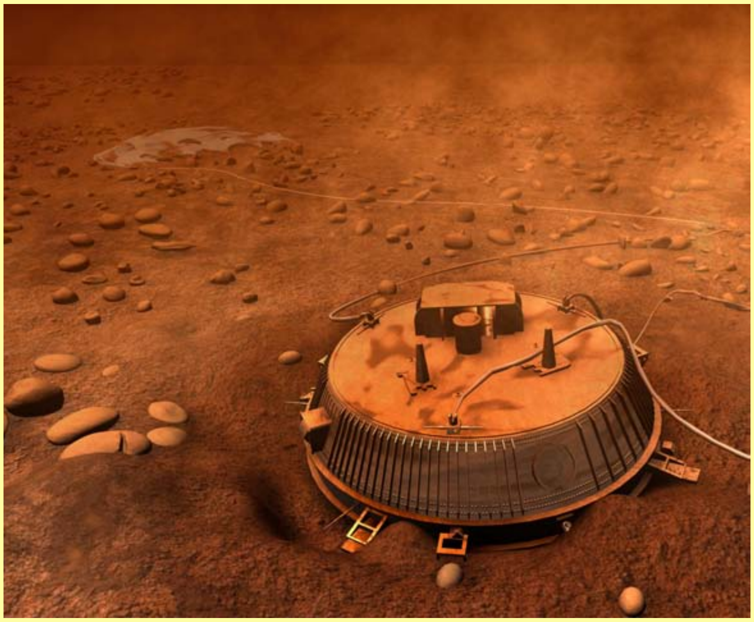
Pioneer Venus Orbiter 1978–1992. Venus orbiter with comprehensive payload for remote sensing and in-situ aeronomy.

1. Pioneer Venus showed that the greenhouse effect operates much more efficiently on Venus. Data from the four atmospheric probes lead to a greenhouse model that closely matches the observed vertical temperature profile. However, Pioneer Venus did not determine the long-term stability of the current temperature or climate.
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, although not all altitudes were probed at all parts of the cycle.
4. Demonstrated the limitations of remote sensing. Little information provided on atmospheric components lacking spectral signatures, on the nature of the middle and deep atmosphere, and on the surface and interior.

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.
2. Combining Huygens descent images with remote observations allowed identification of dune fields by their distinctive color. This, in turn, yielded the exact lander location, ground truth for remote sensing, and provides regional context for the landing-site measurements.
3. Radar identification of fields of linear dunes on Titan allows comparisons to similar features on Earth, Venus and Mars. Comparisons to earth analogs in turn increases understanding of surface processes on both bodies.

Pioneer Venus Orbiter and Probes.



Artist's Conception of Huygens Probe (Courtesy of ESA).

The nature of geologic and atmospheric processes that stabilize climate, the evolutionary effects of impacts, and the ways in which surface composition, internal makeup, and geologic history can sustain habitable environments are among the fundamental issues needed to address these themes. Factors that led uniqueness of each of the terrestrial planets include their bulk compositions, distances from the Sun, internal structures, impact histories, as well as the histories of their water and other volatiles. The analysis of Venus' surface in seven locations by the Soviet Landers in the 1970s and the isotopic measurements of volatiles on these landers and the Pioneer Venus Probes provide some but not all of the information for the geochemical constraints on Venus' evolutionary history. Thus, the NRC report called for investigations relating to bulk composition and solar-distance effects including:

- Elemental and mineralogical surface composition,
- Noble gas composition of the atmosphere,
- Oxygen isotope composition of the atmosphere and surface, and
- Interior (mantle) composition.

For understanding the internal structure of Venus' young surface and the lack of a significant dynamo-generated magnetic field, this report called for investigations of:

- Horizontal and vertical variations in internal structure,
- Compositional variations and evolution of crusts and mantles,
- Major (internal) heat-loss mechanisms, and
- Major core characteristics.

Resurfacing in the last billion years has obscured the impact history of Venus when compared to the Moon, Mars, and Mercury. Thus, this report called for studies of Venus' past impact history to determine:

- Large impactor flux in the early solar system,
- Global geology, and
- Evolutionary effects of impacts including orbital dynamics.

This report noted that the volatile inventory for Venus is known except for minor species. As the existing data have large error bars, this report calls for further investigations such as:

- Measurements of noble gases and stable-light isotopes, and
- Composition of magmatic volatiles (if present).

Regarding questions about the processes that shape Earth-like planets, the effects of clouds, volcanism and tectonism on climate and its stability, and the active internal and external processes that establish atmosphere and surface conditions clearly apply to Venus. Although Venus does not have Earth-like plate tectonics at present, it is unknown whether or not it is still volcanically active.

Vignette 2: Russian Missions to Venus

In 1961 the Soviet space program initiated an extensive exploration of Venus including atmospheric probes, landers, orbiters, and balloon missions. This program produced many successful missions and provides insights on how to survive and conduct experiments in the Venus environment. The Venera 1 impactor was the first spacecraft that actually landed on another planet; Venera 13 survived on the surface for 127 minutes, which is still unmatched by any other spacecraft at Venus; and the VEGA balloons demonstrated the capability of balloons for aerial exploration.

Spacecraft	Date	Type of Mission
Venera 1	1961	Impactor; spacecraft sealed and pressurized with nitrogen
Zond 1	1964	Probe and main bus; entry capsule designed to withstand 60 to 80°C, and 2 to 5 bars
Venera 2 & 3	1965	Probe and main bus; entered the atmosphere of Venus; designed for 80°C / 5 bar
Venera 7	1970	First to soft land on surface; parachute failure, rough landing, landed on its side; 55 minutes descent / 23 minutes on surface
Venera 8	1972	Performed as designed; soft-lander; 55 minutes descent / 50 minutes on surface
Venera 9	1975	Orbiter (moves out of radio range); soft-lander; first to return photos of surface; 20+55 minutes descent / 53 minutes on surface
Venera 10	1975	Orbiter (moves out of radio range); soft-lander; 20+55 minutes descent / 65 minutes on surface
Venera 11	1978	Flyby, soft-lander; 60 minutes descent / 95 minutes on surface
Venera 12	1978	Flyby, soft-lander; 60 minutes descent / 110 minutes on surface
Venera 13	1981	Orbiter, soft-lander; first color images of surface; 55 minutes descent / 127 minutes on surface
Venera 14	1981	Orbiter, soft-lander; 55 minutes descent / 57 minutes on surface
Venera 15	1983	Orbiter with radar mapper
Venera 16	1983	Orbiter with radar mapper
Vega 1	1984	Flyby, atmospheric balloon probe (international)
Vega 2	1984	Flyby, atmospheric balloon probe (international)

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

For the climate topics, this report called for investigations that determine:

- The general circulation and dynamics of the atmosphere,
- The atmosphere composition including trace gases and isotopes,
- Radiation transfer and cloud effects in the atmosphere, and
- Processes and rates of surface-atmosphere interactions.

For the internal processes, this report called for investigations of:

- Current volcanic and/or tectonic activity,
- Absolute ages of the surface,
- Magnetic fields and their relationships to the surface, atmosphere, solar-wind interaction, and
- Processes in the uppermost atmospheres.

Finally, the fate awaiting Earth has been linked to Venus because of a new understanding of greenhouse gases (including those contributed by volcanism) and because Venus is a model for an un-magnetized Earth. Relevant investigations pertaining to the future of Earth and other terrestrial planets include:

- Characterizing the greenhouse effect,
- Assessing volcanic activity,
- Searching for the presence of volcanic gases, and
- Evaluating solar-wind impact effects.

To address these items, the inner-planets panel of the NRC Decadal Survey concluded that a Venus In-Situ Explorer (VISE) was their highest priority choice for the next Venus mission. This New Frontiers class mission would have measurement objectives of:

- Atmosphere composition including trace gases and isotopes,
- Noble gas isotope abundances,
- Meteorological information,
- Cloud-level winds,
- Near-infrared surface images at 10 km and closer ranges,
- Composition and mineralogy of a core sample, and
- Information on surface weathering.

Vignette 3: 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 the USSR'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 EUV 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 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. As well, 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 'aeroving" the distant skies of Titan and the many gas giants of the outer-solar system.

This array of measurement objectives was envisioned to be accomplished by a mission involving an aeroshell entry, passive insulation, and a rapid sample-acquisition system. Possible instrumentation included a neutral-mass spectrometer, a meteorological package, radio tracking of balloon(s) for wind measurement, and a landed package with a near-infrared camera, a surface composition probe, imaging microscope, and a mineralogy analyzer. This report noted that the technologies developed for VISE would be key to a subsequent high priority Venus Sample Return (VSR) mission. It was also noted that it would be impossible to obtain information such as rock ages, or conclusive results on isotope ratios and trace-element abundances without a sophisticated laboratory analysis of Venus return samples.

b. NASA's 2006 Solar System Exploration Roadmap

Subsequent to the National Research Council Decadal Report, NASA commissioned a new Solar System Roadmap Study [3] to establish planetary-mission planning and priorities over the next 25 years. While revisions to these NASA roadmaps occur from time to time to update the science priorities and build upon new discoveries and technologies, they are used as an official guide in targeting technology-development and selections of investigations. Planetary exploration is carried out using both strategic missions, defined primarily by these roadmaps, as well as by the Principal Investigator-led Discovery and New Frontiers missions that are conducted by a lead investigator and his/her team.

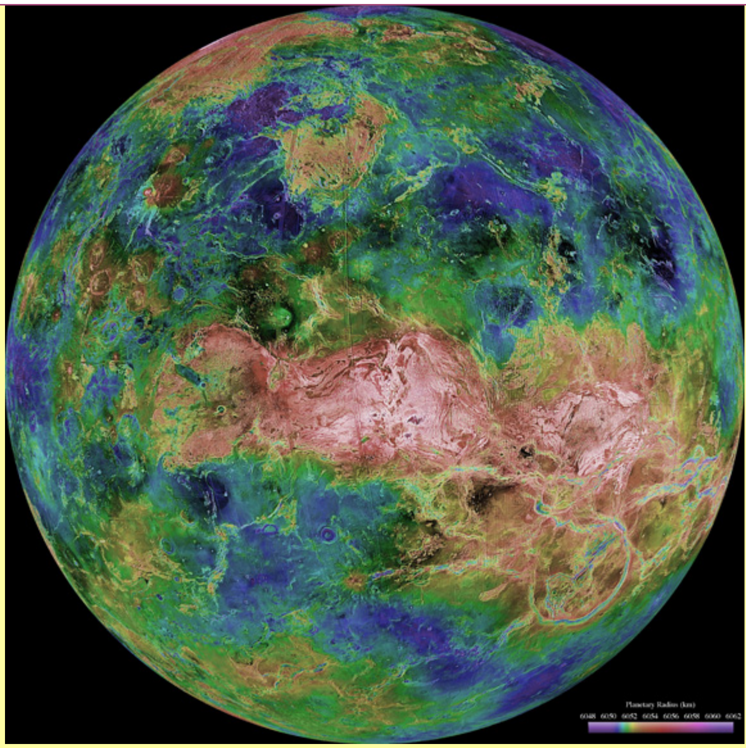
The lower-cost Discovery program welcomes the proposal of mission concepts with any targeted planetary science focus, while the New Frontiers program solicits mission proposals addressing one of several specific high-priority science goals chosen by NASA based on its assessment of the scientific advice received. The planned strategic missions are enabled by investments in both Science Definition Teams and technology developments tailored to their measurement goals and architectures.

NASA's 2006 Solar System Roadmap [3] had planetary habitability as its guiding theme. The main science questions for the Venus mission were identified as:

1. How did the Sun's family of planets and minor bodies originate?,
2. How did the Solar System evolve to its current diverse state?,
3. What are the characteristics of the Solar System that led to the origin of life?, and
4. How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?

The first question can be addressed by comparative studies of climate evolution and Venus' surface-atmosphere interactions. The second question can be addressed by determining the chemical and isotopic composition of Venus' surface and atmosphere, seeking evidence for a past ocean in possible granitic and/or sedimentary rocks, and searching for hydrated silicates and oxidized iron and other climate-related deposits or alterations. The third and fourth questions regarding the origin and evolution of possible past life-forms could similarly be addressed with samples that might contain isotopic, chemical, or structural signatures of biological specimens or processes.

Vignette 4: Magellan



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

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 surface of Venus, with a resolution of approximately 100 m. Altimetry and radiometry data also measured surface topography and electrical characteristics, and a global-gravity map was obtained. The mission terminated in October 1994, following 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 in the form of 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. The random nature of the Venusian impact-crater population prevents its use in age-dating surfaces, unlike on most other bodies in the solar system. The mean surface age is estimated to be ~500 My–1 By, but debate ensued over whether the entire surface was resurfaced in a catastrophic event approximately 500 My ago, or if it has been 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.

The Roadmap notes that the history of water and climate on Venus, including the timing and fate of a possible early ocean, could be investigated with in-situ measurements prior to a sample return. In particular it endorses the idea of a VISE mission involving a brief visit to the surface to obtain samples, followed by sample analysis aloft in a balloon-borne robotic laboratory. A flagship Venus Mobile Explorer (VME) mission was proposed as the follow-on to VISE possibly implemented via floating platforms rather than rovers. Whereas VISE would survive for only a few hours, VME would have to operate for days to weeks. VME would, in turn, enable a subsequent Venus Sample Return mission.

Both VISE and VME need technological developments to carry out their desired measurements at the high temperatures and pressures, and corrosive environment associated with Venus' lower atmosphere and the surface. The Roadmap identifies several enabling technologies including:

- Radioisotope-power systems that can operate at the 460ºC near-surface temperatures,
- Thin metal balloons that would provide buoyancy and mobility and survive under the harsh conditions,
- Thermal-control systems and pressure vessels to contain instruments and electronics, and
- High-temperature electronics and sample-acquisition mechanisms.

Development of instrumentation for mineral and isotopic analyses that are sophisticated and accurate enough to produce answers to the key questions, and can operate semi-autonomously on a balloon platform, is also a challenge. The Roadmap noted that the technology developments tested on VISE could determine the readiness for the VME mission. Thus, the New Frontiers VISE mission would be a critical-technology demonstration mission as well as a science mission.

c. *NASA Science Plan*

The NASA Science Plan [6], developed by a subgroup for the NASA Advisory Council (NAC) took inputs from the Decadal Survey and Solar System Exploration Roadmap to synthesize a grand vision for NASA science missions and supporting programs as a whole. Reports from community groups such as VEXAG were also resources for this effort. As with the Solar System Roadmap, the guiding theme for the overall vision in this 2006 science plan is habitability. In solar-system exploration terms, this translated to five main science questions and four associated research objectives. The science questions are:

- How did the Sun's family of planets and minor bodies originate?,
- How did the solar system evolve to its current diverse state?,
- What are the characteristics of the solar system that led to the origin of life?,
- How did life begin and evolve on Earth and has it evolved elsewhere in the solar system?, and
- What are the hazards and resources in the solar-system environment that will affect the extension of human presence in space?

Vignette 5: 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, ionophere, and into space. In particular, Venus Express is the first Venus orbiter to utilize the new tool of nighttime near-infrared spectroscopic imaging to regularly map the structure and movement of clouds and gases in the hostile depths of Venus below the obscuring upper-level clouds, thereby obtaining new insights into the planet's enigmatic circulation, dynamic meteorology and complex chemistry. This novel spectroscopic tool—embodied on Venus Express as the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS)—maps both (1) the structure and movement of clouds at three different levels (~50-km altitude on the nightside, and 59- and 70-km altitude on the dayside), and (2) the abundances of a plethora of chemically-reactive species, including water (H_2O), sulfur dioxide (SO_2), carbon monoxide (CO), and OCS—at a variety of altitudes in the deep atmosphere below the clouds. It also observes the hot (~740 K) surface of Venus near 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 ground toward Earth. As one facet of the Venus Radio 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 periodically 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 micron 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' nightside 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, known as SPICAV and SOIR, respectively, regularly observe the limb of the planet in solar occultation from close range (typically less than 1000 km), thereby producing high-resolution (~5-km) vertical profiles of a variety of light-absorbing species, including H_20, CO and SO_2. VIRTIS observes nighttime emissions produced by the recombination of photochemically-generated oxygen atoms into oxygen molecules, thereby revealing key day-to-night circulation flows near the 120-km level. As well, VIRTIS maps the nighttime temperatures of the atmosphere at 5 km vertical resolution from 60 to 90 km, providing key constraints on the thermal winds in this region. Enigmatic polar features known as Polar Dipoles at both the south and north poles—suspected to be 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. 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 both ASPERA and MAG from a variety of positions around Venus then reveal how Venus interacts with the Sun's magnetosphere and solar wind. As well, ASPERA measures ionized atoms such as hydrogen and oxygen kicked off the planet's tenuous uppermost atmosphere by the solar wind, thus providing a key constraint on the loss of elements responsible for the extremely dry state of Venus today.

Venus Express has generated more than 1 Terrabit of data to Earth in its first 500 days of operation. Recent Venus Express VIRTIS results are given in Vignette 6, following Section 2.

The associated research objectives to address these questions are (some are abridged) were:

- Learn how the Sun's family of planets and minor bodies originated and evolved,
- Understand the processes that determine the history and future habitability in the solar system,
- Identify and investigate past and/or present habitable environments, and determine if there is or ever has been life elsewhere in the solar system, and
- Explore the space environment to discover potential hazards to humans and to search for resources.

The expected similarity yet disparate natures of present Venus and Earth was noted with Venus considered to be an excellent laboratory for understanding the evolution of habitable planets. A prospective New Frontiers VISE mission that would spend a short time on the surface and provide some of the technological and scientific groundwork for sample return, was called out. A subsequent detailed surface exploration by a Venus Mobile Explorer (a strategic mission recommended by the Solar System Roadmap) would lead to a sample-return mission. The significant technical developments related to in-situ Venus lower atmosphere and surface exploration are clearly drivers for these future Venus missions.

1.4 Current Status of NASA's Support of Venus Research

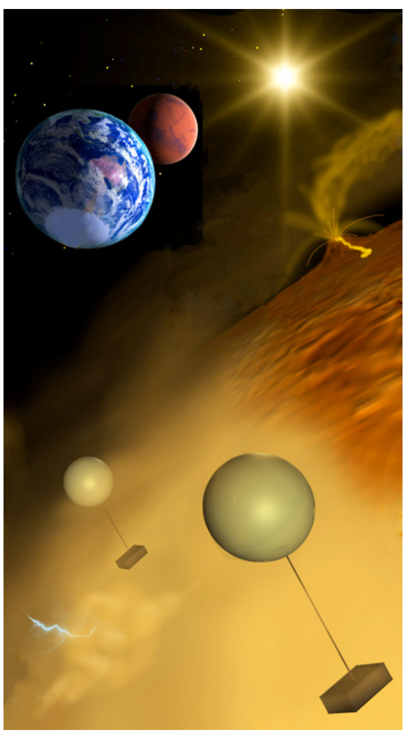
The Crisp (2002) paper [1] appended to the Solar System Decadal Survey, mentioned earlier, provides a good summary of where Venus science stood prior to ESA's Venus Express Mission. Their assessment was that after the observations of the Pioneer Venus Orbiter (PVO) and Magellan, critical knowledge of the interior structure, surface composition, lower and middle atmosphere, and atmosphere-surface interactions is minimal to missing. Although Magellan exposed the resurfacing enigma, we don't know why it happened, over what time period it occurred, and what the larger implications and consequences are. Similarly, PVO found possible evidence of active volcanism, but the results are only suggestive. In the interest of brevity, we refer the reader to the Crisp (2002) paper [1] for the details and focus here on programmatic issues related to the community's ability to expand our Venus knowledge base.

NASA has invested in the new observational resource provided by ESA's Venus Express mission by supporting Participating Scientists, Interdisciplinary Scientists, and Support Investigators. Venus Express data will be deposited in an open European data archive that parallels the PDS. These data are available to a new group of investigators, especially those in atmospheric science areas that were not addressed during the PVO or Magellan missions.

In the past, Venus data analysis has benefited from targeted Venus Data Analysis Programs (VDAP) within Research & Development (R&A). Such programs focus on selected topics of great interest to NASA, such as exploiting new observations toward increasing knowledge needed for informed exploration planning. It is important to exploit the data from current, past and future missions to answer the science questions above. The challenge is how to support the key Venus data analysis and interpretation in light of NASA's R&A program's budgetary constraints. Of the ~1000 NASA Planetary R&A investigations funded per year, about 30 are currently for Venus-focused investigations. Although a few of these are dedicated to maintaining data archives, the majority are for science efforts that run the gamut from tectonism to climate change.

Another new direction for Venus research is that of understanding global change on Earth via the comparison of climatology of these two planets. Global warming on Earth has raised consciousness about the potential instability of climate systems. Also, a key finding from the recent Chapman Conference [4, 5] is that Venus may have been habitable for much of its history. Thus, Venus provides climatologists with an opportunity to test state-of-the-art models simulating the mechanisms and processes that led to Venus' extreme climatology. NASA and VEXAG are pursuing an increased dialogue between Earth and Venus science communities. A new comparative-climatology initiative cosponsored by NASA'S Earth and Planetary science programs would motivate and encourage work in this increasingly-relevant area.

In summary, NASA's investments in the analysis of Venus Express results, the continued study of Venus geology and geophysics, and understanding Venus atmosphere evolution are needed to understand Venus and provide for the planning of future missions. In parallel with these, there will be a need to understand how future Flagship missions can address the outstanding questions about Venus.



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

2. VEXAG GOALS, OBJECTIVES, AND INVESTIGATIONS

With the context provided by the aforementioned recent studies and reports, VEXAG has adopted a set of three GOALS for Venus Exploration. While these closely mirror the topics and themes of the other reports, they were chosen by the VEXAG community to provide a better framework for their analysis of specific-exploration plans.

1. Origin and Early Evolution of Venus: How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and conditions of habitable environments on Venus and similar extrasolar systems? (which correponds to Solar System Roadmap Objectives 1, 2, 3, 4.)
2. Venus as a terrestrial planet: What are the processes that have shaped and still shape the planet? (which correponds to Solar System Roadmap Objectives 1, 2, 4.)
3. Implications for the Earth: What does Venus tell us about the fate of Earth's environment? (which correponds to Solar System Roadmap Objective 2, 4.)

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

The surface of Venus appears to have been shaped, for the most part, within the geologically recent past, probably within the past 1 billion years. Venus' surface may contain evidence of the planet's earlier history and origin, possibly accessible through a more complete characterization of the surface than possible previously, a deeper understanding of the nature and evolution of the interior dynamics, and detailed-chemical measurements of the composition of the atmosphere (in particular, the noble gases and their isotopes). Of particular interest is the possibility that Venus, early in its history, had long-lived oceans and a climate amenable to the development and evolution of living organisms—these hypotheses are not excluded by current knowledge. This Goal involves the search for evidence of the ancient history of Venus (prior to around 1 billion years ago) including evidence in the rock record of earlier wetter and cooler periods, chemical tracers in the atmosphere that provide timing on degassing and the development of runaway greenhouse, and biological markers of organisms in the atmosphere.

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

Although Earth and Venus are 'twin' planets in size and mass, Venus' surface is clearly hostile to carbon-water-based organisms. Venus' atmosphere, which is far denser than Earth's, is composed mostly of carbon dioxide with abundant sulfur oxides and with a conspicuous deficit of hydrogen. Venus' atmosphere moves (everywhere but within a few hundred meters of the surface) at hurricane speeds—in excess of 60 times planetary rotation speed near the cloud tops. How a planet that revolves more slowly than a normal walking speed can generate such winds globally is an enigma. Venus' surface is composed mostly of familiar igneous rocks (basalt) at an average temperature of ~460 ºC, precluding the presence of liquid water. Venus' highlands are mantled by deposits of an electrically-conductive or semiconductive material. Venus' geologic processes are also largely dissimilar from those on Earth, aside from volcanic eruptions. The surface of Venus appears to have been resurfaced or reworked within the past 1 billion years, obscuring possible signatures of earlier geological activity. The nature and duration of this resurfacing remains enigmatic. Subsequent to resurfacing, styles of tectonism and volcanism evolved as the near surface of the planet cooled, so that the thermal/dynamic regime of the planet is now of deep convection under a stagnant or sluggish lid. There is no manifestation of the global-plate tectonic processes like those on Earth. While the general sequence of these events is known in general terms, there remains considerable debate on the evolution of tectonic and volcanic processes. Although some atmospheric data suggest that Venus is still volcanically active, we have no other direct evidence of current volcanic or tectonic activity. Exploring and characterizing processes on and in Venus can help us understand dynamical, chemical, and geologic processes on alien worlds throughout the universe.

Goal 3. What Does Venus Tell Us About the Fate of Earth's Environment?

Although the terrestrial planets formed at about the same time within the inner solar system, from similar chemical and isotopic reservoirs, they have followed very different evolutionary paths. In particular, Venus and Earth, which formed at similar distances from the Sun and have nearly identical masses and densities, are vastly different in their atmospheres, surface environments, and tectonic styles. It has been suggested that Venus may have been more Earth-like earlier in its history but evolved to its current state, and that Earth may ultimately transform to a hot dry planet like Venus. Thus, understanding the interior dynamics and atmospheric evolution of Venus provides insight into the ultimate fate of Earth.

2.1 Matrix of Venus Exploration Goals, Objectives, and Investigations

For each of these 3 goals the OBJECTIVES within each GOAL, and the INVESTIGATIONS needed to address each OBJECTIVE have been developed. These arose from interactions at VEXAG meetings in which VEXAG's three focus groups on the atmosphere, the solid planet, and technologies met. Note that at this point no effort has been made to remove redundancy or to show that certain measurements map to several objectives and goals. This mapping is provided in a subsequent chart.

Within each GOAL, there is a series of OBJECTIVES, with priority rankings based on which must be completed first and on scientific importance. These rankings are fluid as objectives are fulfilled and new discoveries occur. Within each OBJECTIVE there are INVESTIGATIONS that are collectively needed to achieve that objective. These INVESTIGATIONS are generally scientific, and may be addressed by single or multiple missions and/or instruments. Significant technology development may be required for the development of instruments capable of optimally performing the INVESTIGATIONS. These INVESTIGATIONS are listed in priority order within each OBJECTIVE. While a large number of potential INVESTIGATIONS are identified to address the GOALS for Venus exploration, some prioritization of activities is required. Such prioritization will only occur through consensus building within the scientific community, and must be revisited frequently as exploration continues and new technologies come online.

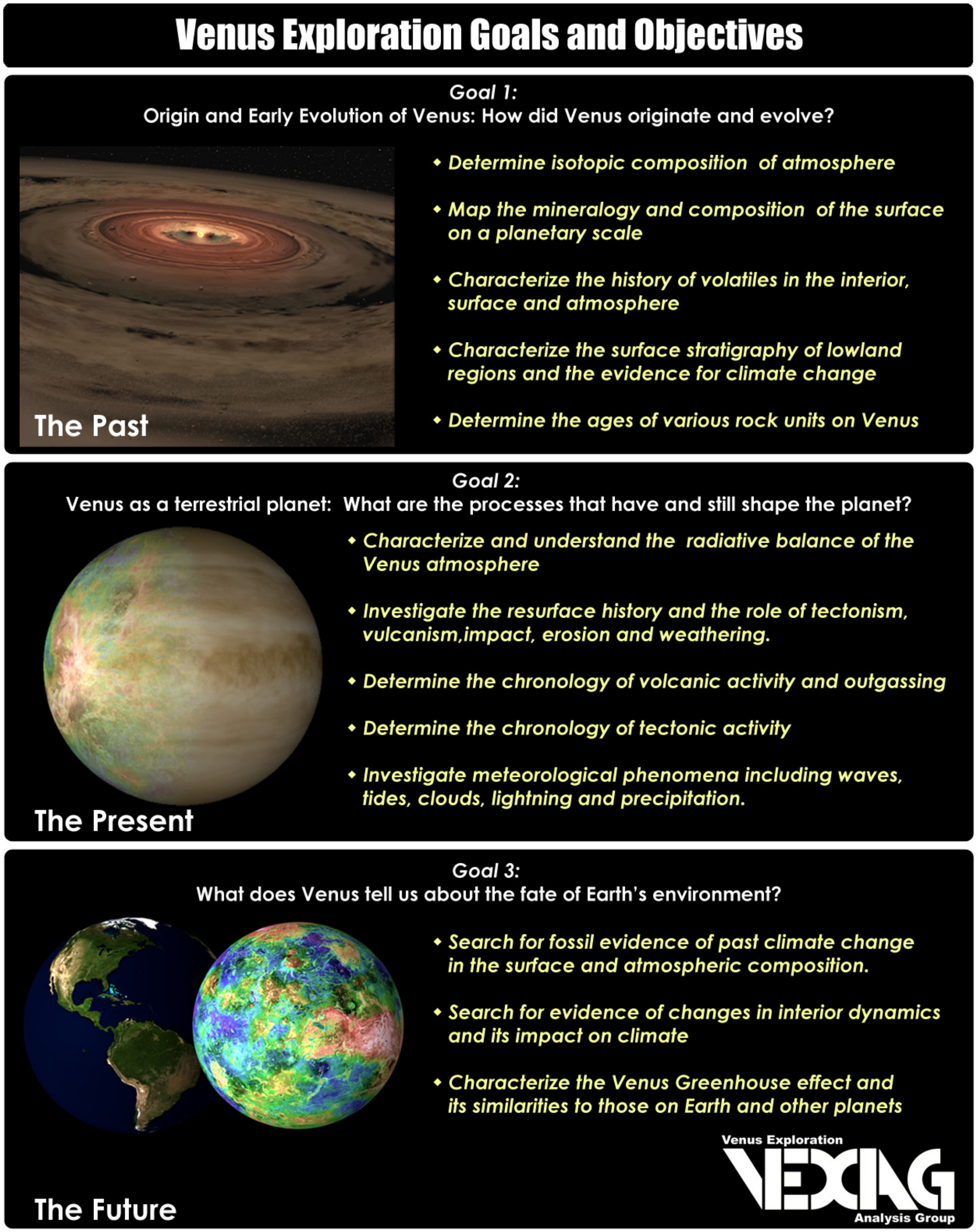


Figure 2-1. An Overview of the Venus Exploration Goals and Objectives.
These VEXAG goals relate to the past, present, and future.

VEXAG Goals, Objectives, Investigations and Priorities: 2007
Within each Goal, Objectives are listed in approximate priority order, with highest priority at the top.
Within each Objective, Investigations are listed in approximate priority order, with highest priority at the top.
Goal 1. Origin and Early Evolution of Venus: How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and conditions of habitable environments on Venus and similar extrasolar planets?
Objective 1: Determine the elemental and isotopic composition of the atmosphere to identify earlier epochs of Venus' history, and clues to Venus' origin, formation and evolution.
Investigation 1: Characterize noble gases and isotopic composition with a precision sufficient to enable understanding of Venus' origin and early evolution, especially measurements of the isotopes of xenon and krypton. By comparing with Earth and Mars, elucidate the origin, formation and early history of the inner solar system, especially our home world. Characterize both bulk abundances and isotopic ratios of Ar, Kr and Xe to ± 5% accuracy to determine the roles of cataclysmic events early in Venus' and Earth's history, including collisions by large icy planetisimals, massive comets, and atmospheric blowoff by extreme solar EUV radiation. Characterize bulk Ne and its three isotopes to ±5% accuracy to determine whether Earth and Venus began as fraternal twins, formed from similar materials in similar environments. Characterize radiogenic helium (^{4}He), argon (^{40}Ar) and Xe isotopes, formed by radioactive decay in Venus's interior, with $^{40}Ar/^{36}Ar$, $^{4}He/^{3}He$ and Xe isotope ratio accuracies of ± 5%, to determine the rate of interior outgassing, thereby elucidating geophysical processes deep within Venus.
Investigation 2: Determine atmospheric H/D, $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{34}S/^{32}S$ and $^{13}C/^{12}C$ to a precision of ±10%.
Investigation 3: Determine isotope ratios H/D, $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{34}S/^{32}S$ and $^{13}C/^{12}C$ to a precision of ±10% in solid samples where possible.
Investigation 4: Characterize gases trapped in rocks for evidence of past atmospheric conditions. It is possible that ancient rocks would have trapped within them, as they formed, aliquots of the then-present Venus atmosphere. By comparison with the present-day Venus atmosphere, this information would be important for constraining the long-term evolution of Venus' climate.
Objective 2: Map the mineralogy and chemical composition of Venus' surface on the planetary scale for evidence of past environmental conditions (e.g., cooler and wetter) and for constraints on the evolution of Venus' atmosphere.
Investigation 1: Characterize the surface materials of Venus, at multiple sites, in terms of their major element chemical compositions and the chemical compounds (i.e., minerals) in which those elements are sited. This information is fundamental to constraining: (1) the chemical and geological nature of Venus' surface materials (e.g., basalt, granite, sediment), and the processes responsible for those materials; and (2) surface-atmosphere interactions, and their potential for modifying the atmosphere composition.
Investigation 2: Assess the petrography (shapes, sizes, and inter-relationships of mineral grains) and petrology (formation characteristics and processes) of surface rocks. The investigation calls for spatial and textural characterization of surface materials, in concert with chemical and mineralogical characterization (see above). This information is needed for interpretation of chemical and mineralogical characterization (see above) in terms of physical and chemical processes of rock formation and alteration.
Investigation 3: Characterize the temporal evolution of the Venus surface, both in terms of relative chronology and absolute ages of formation. This information is needed for interpreting the planetary and tectonic significance of surface materials (characterized above), and for determining the long-term climatic evolution of the planet.

Objective 3: Characterize the history of volatiles in the interior, surface and atmosphere of Venus, including volatile additions due to cometary impacts, degassing and atmospheric escape, to understand the planet's geologic and atmospheric evolution.
Investigation 1: Determine the physical properties and mineralogy of rocks located in a variety of geologic settings. These bulk properties are indicative of the temperature, pressure, and chemical setting under which the rock formed. This information would significantly constrain the nature of crustal volcanic and tectonic processes, their relationship to interior processes, and how those processes have evolved over time.
Investigation 2: Characterize noble gas isotopic ratios (e.g., isotopic abundances of radiogenic argon generated by radioactive decay of potassium in the planet's interior) to constrain the evolution of the interior and atmosphere. Characterize radiogenic helium (^{4}He), argon (^{40}Ar) and Xe isotopes, formed by radioactive decay in Venus' interior, with ^{40}Ar/^{36}Ar, ^{4}He/^{3}He and Xe isotope ratio accuracies of ±5%, to determine the mean rate of interior outgassing over Venus' history.
Investigation 3: Assess surface geomorphological, geochemical, and geophysical evidence of evolution in volcanic styles. Determining the role and extent of volcanism throughout Venus' history will constrain the planet's interior evolution, crustal development, and atmospheric formation.
Investigation 4: Determine high-altitude neutrals and ions to diagnose the escape processes related to photochemical and solar-wind interaction-related escape processes, especially for oxygen. Neutral oxygen is brought to high altitudes by exothermic dissociative recombination in the ionosphere. When it becomes ionized it can escape if it is exposed to the electric fields generated by the solar-wind flow and interplanetary magnetic field. This process is probably the main route by which Venus has lost oxygen over time, following the cessation of impact erosion and hydrodynamic escape, although sputtering by the ions that impact the exobase instead of escaping can add related neutral oxygen escape. If the dependence on variables such as solar variations can be understood, the potential of these for playing a key role in removing oxygen left over from an early ocean can be assessed.
Investigation 5: Assess signatures of crustal magnetization to constrain the history of the magnetic field.
Investigation 6: Measure stable isotopes in minerals to constrain volatile reservoirs in the solid planet.
Investigation 7: Characterize gases trapped in rocks for evidence of past atmospheric conditions. It is possible that ancient rocks would have trapped with in them, as they formed, aliquots of the then-present Venus atmosphere. By comparison with the present-day Venus atmosphere, this information would be important for constraining the long-term evolution of Venus' climate.
Investigation 8: Characterize gas emissions from volcanos, in terms of chemical compositions, chemical species, and mass flux over time. This information is fundamental to understanding the current composition of Venus' atmosphere, for extrapolating its composition back in time to past epochs, and for understanding the volatile load and characteristics of Venus' interior.
Investigation 9: Determine relative and absolute ages for surface units. Constraining the formation age of surface rocks would be extremely valuable in evaluating the geologic history of the planet. Due to the high-surface temperatures, diffusion of relevant species greatly hampers isotopic-age dating. There are currently no demonstrated techniques that would yield strong constraints on ages within the 1 b.y. estimated range of the current surface. Alternative methods for relative age dating might include analysis of the formation of surface-weathering rinds or the development of a fine-grained regolith.
Objective 4: Characterize stratigraphy that may record geological processes active under different climatic conditions.
Investigation 1: Characterize stratigraphy of surface units through detailed topography and images.

Investigation 2: Characterize subsurface layering and geologic contacts to depths up to several km.
Investigation 3: Determine relative and absolute ages for surface units. Constraining the formation age of surface rocks would be extremely valuable in evaluating the geologic history of the planet. Due to the high-surface temperatures, diffusion of relevant species greatly hampers isotopic-age dating. There are currently no demonstrated techniques that would yield strong constraints on ages within the 1 b.y. estimated range of the current surface. Alternative methods for relative-age dating might include analysis of the formation of surface-weathering rinds or the development of a fine-grained regolith.
Objective 5: Determine the ages of the various rock units on the surface in order to unravel the past geological history of Venus.
Investigation 1: Determine rock ages from multiple sites using appropriate dating schemes.
Investigation 2: Determine relative ages of geologic units (requires higher resolution imagery, at a range of wavelengths, and altimetry).
Investigation 3: Characterize surface exposure ages through measurements of weathering rinds.
Objective 6: Understand the orbital and rotational history of Venus, including its position relative to the solar system "habitable zone", and past planet-atmosphere interactions that may have led to the retrograde super rotation of the atmosphere.
Investigation 1: Determine the moment of inertia and characterize spin-axis variations over time.
Objective 7: Seek evidence for biologic markers, including biogenic-rock structures and/or other physical evidence of biological organisms (e.g., fossils), isotopic anomalies suggestive of biological activity, and chemical equilibria or disequilibria that may suggest biological activity.
Investigation 1: Characterize carbon, sulfur, nitrogen and oxygen isotopes to search for biosignatures in the atmosphere. Determine atmospheric $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{34}S/^{32}S$ and $^{13}C/^{12}C$ to a precision of ±10%.
Investigation 2: Determine abundances of atmospheric sulfur species – OCS, H_2S, SO_2, S_x throughout the atmosphere, including the cloud-forming region, to understand the sulfur cycle.
Investigation 3: Search for and characterize organic compounds (e.g., chlorophyll) especially in the clouds that could harbor extremophiles.
Investigation 4: Characterize sources of chemical disequilibrium in the atmosphere.
Investigation 5: Search for evidence of paleochemical disequilibria.
Investigation 6: Characterize the nature and composition of mode-3 cloud particles. Determine particle size, density, and optical properties from UV to the infrared. Determine composition, especially trace components apart from H_2SO_4 and H_2O.
Investigation 7: Characterize features of surface rocks that may indicate past climate or biogenic processes.
Investigation 8: Characterize the chemical compositions of materials near Venus' surface as a function of depth. This information is important to define the extent and rates of chemical reactions between the atmosphere and the surface, and thus is important in constraining the long-term evolution of the atmosphere.
Objective 8: Understand Venus as one potential analogue for terrestrial extra-solar planets.
Investigation 1: Obtain a complete remote characterization of Venus from UV to radio frequencies at all solar cycles to compare with signatures of extra-solar planets.
Investigation 2: Characterize Venus' long-term evolution to understand terrestrial planets around other stars.

Investigation 3: Model the disk-averaged spectrum as a function of evolutionary history.
Investigation 4: Determine critical factors leading to limits of habitable zones.
Goal 2. Venus as a Terrestrial Planet: What are the processes that have shaped and still shape the planet?
Objective 1: Constrain the coupling of thermochemical, photochemical and dynamical processes in Venus' atmosphere and between the surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles.
Investigation 1: Determine sulfur cycle processes. Measure relevant trace species (e.g., H_2O, SO_2, OCS) abundances over the full extent of cloud altitudes.
Investigation 2: Determine abundances of other reactive species important for understanding thermo-chemical processes (e.g., HCl, HF, SO_3).
Investigation 3: Determine the size, distribution, shapes, UV, visible, and IR spectra of aerosols. Since previous Venus missions show significant variability, vertical profiles should be measured at several locations.
Investigation 4: Characterize the flux of materials emitted from volcanoes, including chemically active and inactive species, aerosols and other particulates, and molten lava. These data are fundamental to characterizing surface-atmosphere coupling on Venus, as all volcanic products can have significant effects on atmosphere chemistry and evolution.
Investigation 5: Determine radiative balance, including cloud and greenhouse-gas opacities over wavelength and solar deposition and thermal emission as a function of altitude, latitude, and longitude.
Investigation 6: Determine role of lightning in generating chemically-active species (e.g., NO_x).
Objective 2: Constrain the resurfacing history of Venus, and the nature of the resurfacing processes, including the roles of tectonism, volcanism, impacts of asteroids or comets, sedimentation/erosion, and chemical weathering.
Investigation 1: Constrain stratigraphy and geologic processes through detailed topography and images.
Investigation 2: Characterize the structure and dynamics of the interior of Venus. Knowledge of the structure and dynamical processes of the interior is crucial for understanding the origin and evolution of Venus as well as surface evolution and the release of volatiles as they relate to interior-climate coupling. Detailed information on the thickness and state of the planet's interior layering will constrain the understanding of the bulk composition, differentiation, the lack of magnetic field (e.g., existence of a liquid outer core and/or a solid inner core), and the processes by which the interior has evolved. Characterization of the current rate of internal activity will place constraints on the mechanisms and rates of recent resurfacing and volatile release from the interior.
Investigation 3: Characterize surface-geologic units in terms of major element chemical compositions, the chemical compounds (i.e., minerals) in which those elements are sited, and isotopic characteristics. This information is fundamental to constraining: (1) the chemical and geological nature of Venus surface materials (e.g., basalt, impact ejecta); and (2) the processes responsible for those materials (e.g., tectonism, volcanism, impact cratering). These facts are part of the resurfacing history of Venus.
Investigation 4: Determine the structure of the crust as it varies both spatially and with depth. Of particular interest is knowledge of the thickness of the crust, intracrustal layering, and how surface-geologic contacts extend into the crust.
Investigation 5: Measure heat flow and surface temperature to constrain the thermal structure of the interior.

Investigation 6: Determine relative and absolute ages for surface units. Constraining the formation age of surface rocks would be extremely valuable in evaluating the geologic history of the planet. Due to the high-surface temperatures, diffusion of relevant species greatly hampers isotopic-age dating. There are currently no demonstrated techniques that would yield strong constraints on ages within the 1 b.y. estimated range of the current surface. Alternative methods for relative-age dating might include analysis of the formation of surface weathering rinds or the development of a fine-grained regolith.
Objective 3: Constrain the nature and timing of volcanic activity on Venus, including thermal evolution, current and past rates of volcanic activity, and the effects of outgassing on atmospheric and interior processes.
Investigation 1: Characterize active-volcanic processes such as ground deformation, flow emplacement, outgassing, or thermal signatures.
Investigation 2: Characterize the structure and dynamics of the interior of Venus. Knowledge of the structure and dynamical processes of the interior is crucial for understanding the origin and evolution of Venus as well as surface evolution and the release of volatiles as they relate to interior-climate coupling. Detailed information on the thickness and state of the planet's interior layering will constrain understanding of the bulk composition, differentiation, the lack of magnetic field (e.g., existence of a liquid outer core and/or a solid inner core), and the processes by which the interior has evolved. Characterization of the current rate of internal activity will place constraints on the mechanisms and rates of recent resurfacing and volatile release from the interior.
Investigation 3: Investigate stratigraphy and geologic processes through detailed topography and images.
Investigation 4: Characterize surface geologic units in terms of major-element chemical compositions, the chemical compounds (i.e., minerals) in which those elements are sited, and isotopic characteristics. This information is fundamental to constraining: (1) the chemical and geological nature of Venus surface materials (e.g., basalt, rhyolite); and (2) volcanic processes that may be responsible for the origins, emplacements, or alterations of surface-geologic units.
Investigation 5: Identify and characterize plumes and other gas emissions from volcanoes, in terms of chemical compositions and species, temporal variations, and mass flux. This information is fundamental to understanding the effects of volcanic input to Venus' atmosphere, for extrapolating its composition back in time to past epochs, and for understanding the volatile load and characteristics of Venus' interior.
Investigation 6: Determine the structure of the crust as it varies both spatially and with depth. Of particular interest is knowledge of the thickness of the crust, intracrustal layering, and how surface-geologic contacts extend into the crust.
Investigation 7: Determine relative and absolute ages for surface units. Constraining the formation age of surface rocks would be extremely valuable in evaluating the geologic history of the planet. Due to the high-surface temperatures, diffusion of relevant species greatly hampers isotopic-age dating. There are currently no demonstrated techniques that would yield strong constraints on ages within the 1 b.y. estimated range of the current surface. Alternative methods for relative-age dating might include analysis of the formation of surface-weathering rinds or the development of a fine-grained regolith.
Investigation 8: Measure heat flow and surface temperature to constrain the thermal structure of the interior.

Objective 4: Determine the nature and timing of tectonic evolution of Venus, including the style and intensity of current activity, and changes in style and intensity through time.
Investigation 1: Characterize the structure and dynamics of the interior of Venus. Knowledge of the structure and dynamical processes of the interior is crucial for understanding the origin and evolution of Venus as well as surface evolution and the release of volatiles as they relate to interior-climate coupling. Detailed information on the thickness and state of the planet's interior layering will constrain understanding of the bulk composition, differentiation, the lack of a magnetic field (e.g., existence of a liquid outer core and/or a solid-inner core), and the processes by which the interior has evolved. Characterization of the current rate of internal activity will place constraints on the mechanisms and rates of recent resurfacing and volatile release from the interior.
Investigation 2: Constrain stratigraphy and geologic processes through detailed topography and images.
Investigation 3: Determine the structure of the crust as it varies both spatially and with depth. Of particular interest is knowledge of the thickness of the crust, intracrustal layering, and how surface-geologic contacts extend into the crust.
Investigation 4: Measure heat flow and surface temperature to constrain the thermal structure of the interior.
Investigation 5: Characterize active-tectonic processes through seismic, ground motion, or detailed image analysis.
Investigation 6: Characterize surface-geologic units in terms of major-element chemical compositions, the chemical compounds (i.e., minerals) in which those elements are sited, and isotopic characteristics. This information is fundamental to constraining: (1) the chemical and geological nature of Venus surface materials (e.g., basalt, impact ejecta); and (2) the processes responsible for those materials (e.g., tectonism, impact cratering). These facts are part of the resurfacing history of Venus.
Investigation 7: Determine relative and absolute ages for surface units. Constraining the formation age of surface rocks would be extremely valuable in evaluating the geologic history of the planet. Due to the high-surface temperatures, diffusion of relevant species greatly hampers isotopic-age dating. There are currently no demonstrated techniques that would yield strong constraints on ages within the 1 b.y. estimated range of the current surface. Alternative methods for relative-age dating might include analysis of the formation of surface-weathering rinds or the development of a fine-grained regolith.
Objective 5: Characterize the meteorological activity in Venus' atmosphere, including convection, cloud formation/dissipation, precipitation, lightning, and sporadic and organized dynamical activity analogous to terrestrial-weather systems. In particular, study the roles local-gravity waves, planetary-scale waves, and solar-induced tides play in producing meteorological activity. Determine whether a common theoretical treatment can be applied to weather on Venus and Earth.
Investigation 1: Determine vertical profiles of condensibles and of the chemical precursors to aerosols. Determine aerosol abundances, size, shapes and spectra.
Investigation 2: Characterize gravity waves near the surface and throughout the atmosphere. Search for and characterize correlations with topographic-surface features.
Investigation 3: Characterize local vertical winds and turbulence associated with convection and cloud-formation processes, especially near and within the middle-cloud region.
Investigation 4: Measure the frequencies and strengths of lightning and associated chemical species (e.g., NO_x).

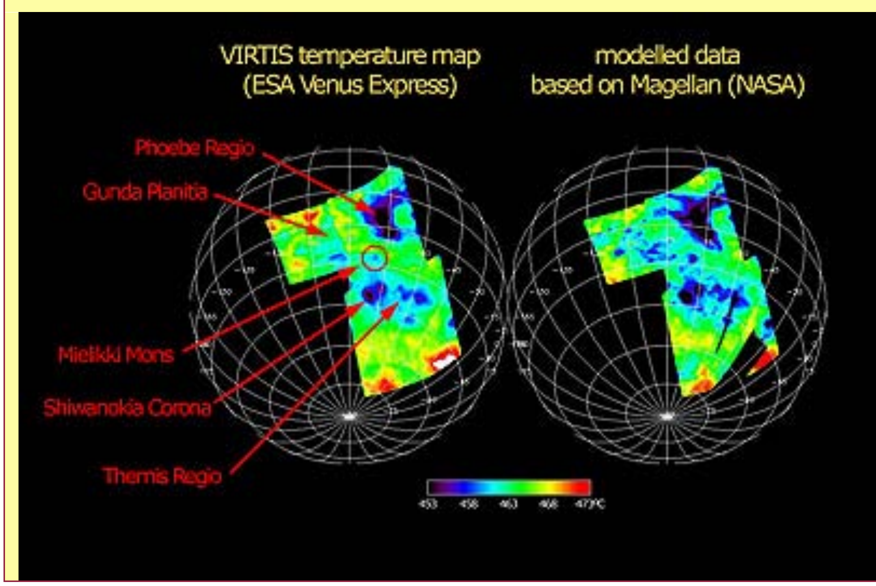
Objective 6: Determine the history of and current state of interior evolution of Venus, including the internal physical, chemical, thermal and dynamical structure, and possible interactions between dynamic and climatic processes.
Investigation 1: Determine interior structure and levels of seismic activity to constrain models of interior evolution. A regional or global network of seismometers could answer several important questions: (1) What is the current level of seismic activity (frequency and magnitude)? How does it vary spatially? What do the focal mechanisms imply about the style of tectonic deformation? (2) What is the crustal thickness, and how does it vary with location? (3) What is the seismic velocity structure of the mantle, and what does this imply about the chemical composition and thermal structure of the mantle? (4) What is the size and physical state of the core?
Investigation 2: Characterize the current structure and evolutionary history of the core to understand whether a geodynamo has ever existed and to obtain insight into the thermal history of Venus.
Investigation 3: Measure the moment of inertia to provide constraints on the internal-density structure, and hence geochemistry, of Venus.
Investigation 4: Measure topography and gravity to high resolution to constrain models of surface feature and interior evolution. The topography of Venus is currently known with a horizontal resolution of 10 to 30 kilometers and a vertical accuracy of 10 to 100 meters. In order to better interpret and quantify the various geologic processes that have sculpted the Venus surface, it is desirable to have a topography map whose horizontal resolution is commensurate with the available radar imagery of the surface (target resolution 1 km or better). Measurements of the gravity field currently provide our only constraints on the subsurface structure of Venus. The horizontal resolution of the current gravity model varies from 350 to 1000 km, depending on location. In order to better connect the gravity observations to the surface geology, a desirable goal is to improve the degree strength of the gravity model to at least spherical-harmonic degree 120 (horizontal resolution 320 km) for all parts of Venus.
Investigation 5: Measure heat flux and surface temperature to constrain the thermal structure of the interior of Venus.
Investigation 6: Measure the magnetic field below the ionosphere to seek evidence for the past existence of a geodynamo.
Investigation 7: Characterize magnetic signatures of surface rock units in multiple environments, with ages (e.g., hafnium/tungsten) to seek evidence of terrains from the earlier history of Venus and possible evidence of a past geodynamo.
Objective 7: Determine the nature of the solar-wind interaction with the ionosphere and its role in volatile loss.
Investigation 1: Determine the composition and flux of escaping neutrals and ions over all energies under all solar wind and solar EUV conditions (See Objective 3, Investigation 3). PVO detected UV emissions from a hot oxygen corona around Venus but the results were not sufficient to determine if a sputtered component was present or not. Similarly, escaping oxygen ions were detected but the measurements were limited by the ion-detector energy range and sampling. Venus Express will continue and extend the escaping-ion measurements but the overall results cannot be evaluated at this time. It will not measure the sputtered component or low-energy ion escape, which may be important.
Investigation 2: Obtain UV measurements of exospheric profiles of O, H and their global variability over a solar cycle. Such measurements can be used together with models to both determine whether the sputtering process is effective and to evaluate the importance and range-of-time variations in the exospheric densities. The oxygen exosphere in particular is the reservoir for the production of the escaping ions and the related sputtering agents.

Investigation 3: Obtain ionospheric-composition profiles and characterize their spatial and temporal variations. The main ionospheric constituent, O^{2+}, is the main source of the hot oxygen exosphere. Other ionospheric-molecular ions also undergo dissociative-recombination interactions that produce minor-species exospheres that can participate in the solar-wind erosion process. By measuring and then modeling the variations in the ionospheric constituents, the physics and chemistry underlying the exospheric supply chain can be understood.
Investigation 4: Monitor magnetic-field and solar-wind plasma and energetic particles over a solar cycle. These external conditions can influence escape rates in a variety of ways including via contributions to particle-impact ionization rates, by limiting the energies of the accelerated-ionospheric ions that participate in sputtering, by heating the upper atmosphere (see Objective 8, investigation 4), and by determining the altitude in the upper atmosphere to which the solar-wind effects can penetrate. The plasma and field conditions relevant to these effects need to be measured in concert with the consequences (the escaping neutrals and ions) to make the relevant physical connections.
Objective 8: Characterize three-dimensional atmospheric circulation to understand the zonal super-rotation, the meridional transport of energy and minor constituents, planetary-scale waves, local surface-induced gravity waves, the global distribution and strength of convective activity, and polar vortex dynamics.
Investigation 1: Measure global-horizontal winds over several Venus days at multiple-vertical levels (day and night) from surface to thermosphere.
Investigation 2: Measure profiles of vertical component of wind at all latitudes and longitudes.
Investigation 3: Measure deposition of solar energy in the atmosphere globally.
Investigation 4: Characterize solar-wind input in the upper atmosphere to understand any heating or momentum deposition that may result from either solar-wind or energetic-particle absorption, related ionization, or ion drag from the penetration of draped interplanetary magnetic fields. Understand how the influences of these processes change as a function of solar activity and solar-cycle phase.
Investigation 5: Determine global vertical-atmospheric temperature profiles.
Investigation 6: Characterize local and planetary-scale waves, especially gravity waves generated by underlying topography.
Objective 9: Characterize the Venus greenhouse effect, including the interplay of chemistry and physics of the atmosphere, especially the clouds.
Investigation 1: Determine distribution of greenhouse gases (H_2O, SO_2, SO_3) and other related species (halogens, sulfur compounds, elemental sulfur, CO_2) that play a direct or indirect role in cloud formation
Investigation 2: Characterize upwelling and downwelling fluxes in the visible to produce a vertical profile of deposition.
Investigation 3: Determine the optical properties of aerosols at several locations.
Investigation 4: Determine vertical-temperature profiles and their variability, with sufficient accuracy to constrain radiation models.
Goal 3. What does Venus tell us about the fate of Earth's environment?
Objective 1: Search for evidence of past global-climate change on Venus, including chemical-and-isotope evidence in the atmosphere, as well as rock chemistry and characteristics of surface weathering. In particular, seek evidence for the presence or absence of past oceans.

Investigation 1: Search for evidence of past habitable environments (including oceans) in the atmosphere and surface regions of Venus.
Investigation 2: Assess surface and near-surface geomorphological and geochemical evidence for climate-change indicators. Determining the evolution of the Venusian climate and possible causalities of climate change would provide an alternative-terrestrial model with potential implications for Earth.
Investigation 3: Assess paleoclimate indicators, stable isotopes (including O, S, H …) that might provide insight into earlier climate regimes.
Investigation 4: Characterize the chemical and isotopic compositions of solid materials at Venus' surface (in concert with characterization of their mineralogy). It is possible that the chemical and isotopic compositions of such materials may preserve evidence of earlier different-dynamic regimes, such as (for instance) recording non-chondritic Th/U ratios that might suggest fractionation in a water-rich system like a plate-tectonic subduction zone.
Investigation 5: Characterize gases trapped in rocks for evidence of past atmospheric conditions. It is possible that ancient rocks would have trapped with in them, as they formed, aliquots of the then-present Venus atmosphere. By comparison with the present-day Venus atmosphere, this information would be important for constraining the long-term evolution of Venus' climate.
Objective 2: Search for evidence of past changes in interior dynamics, volcanics and tectonics, including possible evolution from plate tectonics to stagnant-lid tectonics, which may have resulted in significant changes in the global climate pattern.
Investigation 1: Identify and characterize the morphology of any areas that reflect formation in a geological or climatological environment significantly different from present day. Understanding the nature of these past regimes requires information about the surface and near surface at small spatial scales for the regions of interest.
Investigation 2: Constrain the interior structure of Venus in order to understand the evolution of geodynamics and tectonics.
Investigation 3: Characterize the chemical and isotopic compositions of solid materials at Venus' surface (in concert with characterization of their mineralogy). It is possible that the chemical and isotopic compositions of such materials may preserve evidence of earlier different dynamic regimes, such as (for instance) recording non-chondritic Th/U ratios that might suggest fractionation in a water-rich system like a plate-tectonic subduction zone.
Investigation 4: Search for paleomagnetic signatures that might indicate terrains that are remnants of early stages in Venus evolution.
Objective 3: Characterize the Venus greenhouse effect, including the interplay of chemistry, dynamics, meteorology, and radiative physics in the atmosphere, especially within the clouds.
Investigation 1: Determine abundances of greenhouse gases and other species that play a role in cloud formation. Measure abundances over altitude, especially within the cloud-forming regions. Determine distribution of greenhouse gases (H_2O, SO_2, SO_3) and other related species (halogens, sulfur compounds, elemental sulfur, CO_2) that play a direct or indirect role in cloud formation.
Investigation 2: Determine the optical properties of aerosols at several locations.
Investigation 3: Characterize volcanic outgassing in terms of its chemical composition, chemical species produced, rate of production, and mass flux over time. This information is fundamental to understanding the current composition of Venus' atmosphere and the strength and duration of its greenhouse effect.
Investigation 4: Determine upwelling and downwelling fluxes in the visible to produce a vertical profile of energy deposition.

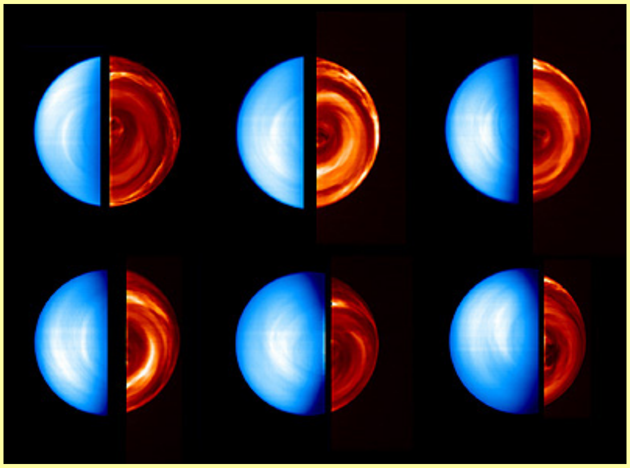
Investigation 5: Determine vertical temperature-profiles and their variability, with sufficient accuracy to constrain radiation models.
Investigation 6: Characterize the chemical compositions of materials at and near Venus' surface as a function of distance from the atmosphere—including characterizing alteration rinds on individual rocks, and characterizing bulk regolith/bedrock alteration with depth. This information is important to define the extent and rates of chemical reactions between the atmosphere and the surface, and thus is important in constraining the long-term evolution of the atmosphere and its greenhouse effect.
Objective 4: Using Venus data, determine the evolution of planetary atmospheres in the absence of a shielding magnetosphere, as may have happened on Earth in the past or may occur in the future.
Investigation 1: Determine current flux of various atmospheric species into space (see Objective 7). The same measurements that lead to an assessment of the loss of Venus' volatiles to space over time provide a measure of the effect of a shielding magnetosphere, although magnetospheres have other loss mechanisms that operate at \ various levels. An evaluation of the possibility that early Venus had a post-accretion, dynamo-generated magnetic field also needs to be considered in evaluating the shielding effects of an active global-dynamo field. Comparisons of escape rates between Venus and Earth need to be made under different solar and interplanetary conditions.
Investigation 2: Determine composition of the upper atmosphere (above ~130 km). Upper atmospheres represent the reservoirs from which escape ultimately occurs. Measurements that help to understand their sources, composition and variability directly impact any studies or models of escape processes.

Vignette 6: Recent Venus Express VIRTIS Results

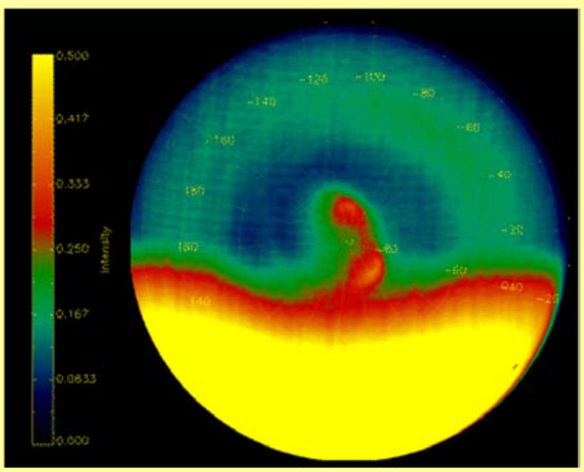


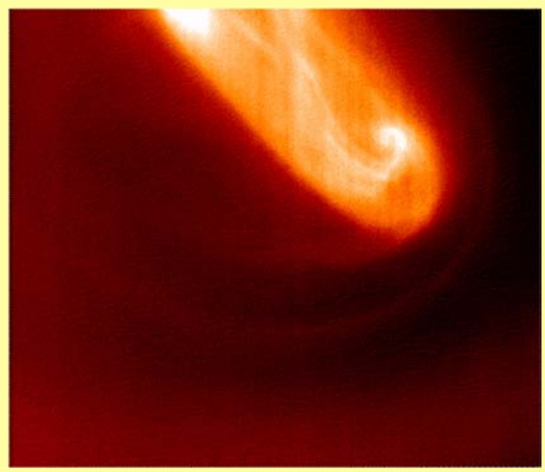
Surface Temperatures.
(left) Black-body temperatures measured for the surface correlate well with topography (right), due to decreases of surface temperature with height. Slight variations in this correlation indicate differences in the emissivity of surface rocks.

Vignette 6: Recent 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 comprised 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-mm 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, which give clues to the processes powering Venus' enigmatic system of super-rotating winds.





Polar Vortex Phenomena. Venus Express confirmed that the south pole has a complex and variable polar dipole. Temperatures near the 60-km level are shown in the nighttime portions of 5-mm images, revealing the dipole to be notably hotter than its surroundings, likely due to compression of descending air. (Bottom half of 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 within a period of about 2.4 days.

3. VENUS EXPLORATION MISSIONS

In the process of discussing the science goals, objectives and investigations for Venus exploration, VEXAG has identified key technologies that must be developed in order to accomplish the needed science measurements. These technologies are also closely linked to the proposed missions and their implementations through various mission architectures. The relevant mission architectures and their science traceability—that is, the mapping of the science goals and objectives against various proposed missions—is discussed in this section and summarized in Table 3-1. Similarly, the enabling technologies and the technology-traceability matrix—where the key technologies are mapped against proposed Venus missions—are discussed in the next section.

3.1 Fifty Years of Venus Exploration—Past and Present Missions

In 1961 the Soviet space program initiated an extensive program for the exploration of Venus, which included atmospheric probes, landers, orbiters, and balloon missions. This program produced many successful missions, which provide information on how to survive and conduct experiments in the Venus environment. Venus exploration by the U.S. 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 a multiprobe mission, called Pioneer-Venus, with the objective of understanding the atmosphere of the planet. These missions, from both the U.S. and Russia, provided groundbreaking-science results and many "firsts". For example, the Venera 1 impactor was the first spacecraft that actually landed on another planet; Venera 13 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; and Magellan mapped 98% of the surface of the planet in the 1990s. A list of these earlier missions is shown in Table 3-1.

Today, Venus Express—an orbiter by the European Space Agency—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. Another orbiter, Planet-C (or Venus Climate Orbiter, VCO) by JAXA, is under development for a 2010 launch. Planned investigations by VCO include surface imaging with an infrared camera; and experiments designed to measure possible lightning and present-surface volcanism.

3.2 Proposed Missions Identified in NASA's SSE Roadmap

Venus exploration is prominently featured in NASA's 2006 Solar System Exploration Roadmap, where proposed missions to diverse destinations—including Venus—are identified under three mission classes. Small Discovery class missions are defined with a cost cap of \$425M (FY06); intermediate New Frontiers class missions currently target a cost cap of \$750M (FY06); while the large Flagship class missions assume funding in the \$1.5B to \$3B (FY06) range.

Table 3-1. Summary of Past and Present Venus Missions.

Spacecraft	Launch Date	Type of Mission
Venera 1	1961	Impactor; Spacecraft sealed and pressurized with nitrogen
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, and 2 to 5 bars
Venera 2 & 3	1965	Probe and main bus; Entered the atmosphere of Venus; Designed for up to 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	Hard-lander; Stopped transmitting at ~20 km (320 °C / 27 bar); 53 minutes descent (Russia)
Venera 6	1969	Hard-lander; Stopped transmitting at ~20 km (320 °C / 27 bar); 51 minutes descent (Russia)
Venera 7	1970	First to soft land on surface; Parachute failure, rough landing, landed on the side; 55 min descent / 23 min on surface (Russia)
Venera 8	1972	Performed as designed; Soft-lander; 55 min descent / 50 min on surface (Russia)
Mariner 10	1973	Flyby en route to Mercury (US)
Venera 9	1975	Orbiter (moves out of radio range); soft-lander; first to return photos of surface; 20+55 min descent / 53 min on surface (Russia)
Venera 10	1975	Orbiter (moves out of radio range); soft-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	1983	Orbiter with radar mapper (Russia)
Venera 16	1983	Orbiter with radar mapper (Russia)
Vega 1	1984	Flyby, atmospheric balloon probe (Russia / International)
Vega 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 – Ongoing mission (ESA)
Planet-C	2010	Venus Climate Orbiter – In development (JAXA)

3.2.1 Discovery Class Missions

The Discovery Program began in the early 1990s and support small PI–led missions. Discovery provides opportunities for targeted investigations and for relatively rapid-flight missions responding to new discoveries. Ten full missions and four Missions of Opportunity (investigations flown on a non–NASA spacecraft) have been selected over the past decade. The Discovery Program is open to proposals for scientific investigations that address any area embraced by NASA's Solar System Exploration Program and the search for planetary systems around other stars. It thereby 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.html.

Vesper, the Latin name for "Evening Star" or Venus, is a proposed mission which was selected for further concept studies from submissions to NASA's Discovery Program 2006 Announcement of Opportunity. If approved, Vesper would observe the planet for two Venus days (about 500 Earth days) to address question related to atmospheric evolution and dynamics (including its super rotation) as well as climate change.

A high-altitude, super-pressure balloon mission was also proposed in 2005 with a main-science objective of resolving fundamental questions of Venus evolution by accurate measurements of the composition of the Venus atmosphere, especially its noble gases. This proposed two 5.4-m diameter spherical super-pressure balloons, carrying a payload primarily consisting of a GC/MS (gas chromatograph / mass spectrometer) and an atmospheric structure instrument. Precise radio tracking could yield understanding of winds and atmospheric dynamics.

3.2.2 New Frontiers Missions

The New Frontiers Program comprises principal investigator-led medium class missions, addressing specific, strategic, scientific investigations that do not require Flagship class missions. The NRC's Solar System Exploration Decadal Survey recommended a prioritized list of five New Frontiers class missions for the decade 2003–2013. The first of these, the Pluto–Kuiper Belt Explorer (New Horizons) mission, was already in Phase A at selection and was launched successfully in January 2006. For the remaining four proposed missions, the NRC Decadal Survey order of priority was: South Pole–Aitken Basin; Jupiter Polar Orbiter with Probes; Venus In Situ Explorer; and Comet Surface Sample Return. Juno, a Jupiter orbiter, was selected for and is currently in a non-competitive Phase A study.

3.2.2.1 Venus In Situ Explorer (VISE)

The Venus In Situ Explorer (VISE) mission concept was envisioned in the NRC Decadal Survey as a balloon mission that would study Venus' atmospheric composition in detail and descend briefly to the surface to acquire samples that could then be analyzed at a higher altitude where the temperature is less extreme. The VISE scientific measurements would constrain models of the Venus greenhouse history and stability as well as the geologic history of the planet, including its extensive resurfacing. Technology demonstrations on VISE would pave the way for a future Flagship class mission to the surface and low atmosphere of Venus as well as a possible subsequent sample-return mission.

New Frontiers Class Mission Concept

Venus In-Situ Explorer

Scientific Objectives

- Composition and isotopic measurements of surface and atmosphere for determining origin and evolution
- Atmospheric dynamics
- Cloud structure, composition, properties
- Acquire and characterize a core sample
- Demonstrate key technologies for VSSR

Exploration Metrics

- Operate in Venus near-surface environment for several hours

Science Payload

- Chemistry package
- UV-VIS-IR cameras; optical package
- Atmospheric instrument (p,T, humidity)
- Gas chromatograph / mass spectrometer
- Instruments to measure elements and mineralogy of surface materials (if lander)
- Radiometer; nephelometer; lightning detector

Technology & Heritage

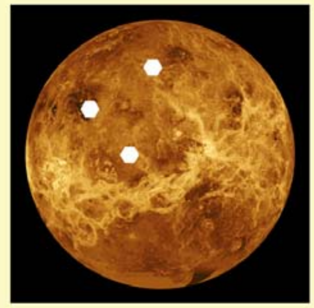
- Extreme environments technologies (pressure vessel, thermal management, corrosion)
- High-temperature electronics
- Sample acquisition and handling in Venus near-surface environment
- Passive insulation; phase change materials
- Component testing in relevant environments

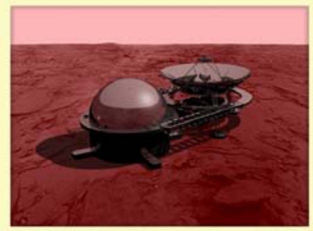
Mission & LV Class

- Intermediate Class Mission
- Launch Vehicle: TBD

Flagship Class Mission Concept

Venus Geophysical Network





Scientific Objectives

- Determine the internal structure and seismic activity of the planet
- Monitor the circulation of the atmosphere

Exploration Metrics

- At least three stations on the surface of Venus
- Operate for at least one Earth year

Science Payload

- Camera, descent imager
- Seismometer network
- Meteorology station with pressure, temperature and wind velocity sensors

Technology & Heritage

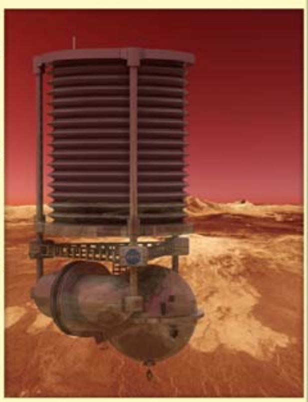
- Extreme-environments technologies (pressure vessel, thermal management, corrosion)
- High-temperature electronics for telecom / high-data volume
- Radioisotope power system w/ active cooling
- Long-duration operations in situ
- Passive insulation and survival technology from VISE

Mission & LV Class

- Flagship Class Mission
- Launch Vehicle(s): TBD

Flagship Class Mission Concept

Venus Mobile Explorer



Scientific Objectives

- Composition and isotopic measurements of surface and atmosphere
- Near IR descent images
- Acquire and characterize core samples at multiple sites
- Demonstrate key technologies for VSSR

Exploration Metrics

- Operate in Venus surface environment for 90 days+
- Range and altitude if aerial vehicle TBD
- Range across surface if rover TBD

Science Payload

- Neutral-mass spectrometer with enrichment cell
- Instruments to measure elements and mineralogy of surface materials
- Imaging microscope

Technology & Heritage

- Extreme-environments technologies (pressure vessel, thermal management, corrosion)
- High-temperature electronics
- Sample acquisition and handling in Venus near-surface environment
- Air-mobility system (e.g., metallic bellows)
- Radioisotope power system w/ active cooling
- Long-duration operations in situ

Mission & LV Class

- Flagship Class Mission
- Launch Vehicle:
  - Delta-IV-H
  - Atlas V

Flagship Class Mission Concept

Venus Surface Sample Return

Scientific Objectives

- Measure isotopic composition of oxygen in surface rocks
- Measure isotopic composition of trace elements to characterize core-and-mantle formation
- Determine the age of returned rocks

Exploration Metrics

- Return samples of Venus rock soil and atmosphere for analysis on Earth
- Mission duration: TBD
- Time on surface: TBD (short lived)

Science Payload

- Camera and Descent imager
- Sample identification as needed
- Sample-acquisition system
- In-situ instrumentation

Technology & Heritage

- Extreme-environments technologies (pressure vessel, thermal management, corrosion)
- High-temperature electronics
- Sample acquisition and handling in Venus near-surface environment
- Multi-stage ascent air-mobility system to lift sample to launch altitude
- Rendezvous and sample-return systems inherited from Mars Sample Return
- Heritage from prior Venus missions: e.g., VISE, Venus Geophysical Network, VME

Mission & LV Class

- Flagship Class Mission
- Launch Vehicle: TBD

Figure 3-1. *Overviews of Future Venus Missions.*

Although the VISE proposal was not selected in the last New Frontiers competition, it is expected that VISE, with a launch in 2015 time frame, would be in the next New Frontiers opportunity (for which the AO is expected by the end of 2008). For further details, see the vignette on a Venus In Situ Explorer concept (Fig. 3-1).

3.2.3 Flagship Missions

Certain high-priority investigations are, by their nature, so challenging that they cannot be achieved within the cost constraints of the Discovery and New Frontiers Programs. With costs significantly larger than those of New Frontiers missions, they represent major national investments that must be selected and implemented in a strategic manner. Examples include comprehensive studies of planetary systems, such as those undertaken by Galileo and Cassini; energy-intensive missions that also require large propulsion systems and launch vehicles; in-depth studies of outer Solar System satellites; and sample return from planetary surfaces. These missions generally require significant focused-technology development prior to mission start, and extended-engineering developments, as well as extensive pre-decisional trade studies to determine the proper balance of cost, risk and science return.

3.2.3.1 Venus Mobile Explorer

A Venus Mobile Explorer (VME) mission concept is proposed in NASA's 2006 Solar System Explorer Roadmap for a new start in the 2015 time frame. This mission was sequenced after the Titan Explorer to permit the opportunity for selecting a New Frontiers class Venus In Situ Explorer (VISE) as a precursor mission. This sequencing provides additional time to develop high-temperature electronics and power technologies needed at the surface of Venus for long-lived missions. VME would take the next logical step in exploring the Venus surface beyond the Magellan mission's epic radar reconnaissance and the presumed VISE. This mission would perform up to several months of extensive measurements at the Venus surface, including a search for granitic and sedimentary rocks; in-situ analysis of the crust for meta-stable hydrated silicates, and measurements of the oxidation and mineralogical state of iron. Together, these landed experiments would provide a determination of how long ago a possible ocean disappeared from Venus, and therefore how long Venus may have had to potentially nurture life. Equipped with visual imaging and a targeted set of geochemical sensors, VME would use the methods of mobile-scientific exploration to sample different surface sites.

Advantages of mobility were demonstrated by the Mars Exploration Rovers (MER), although for VME an air-mobility platform (see Vignette, Fig. 3-1) with long traversing would be preferred over a surface rover, which would have a limited range of hundreds of meters. The MER rovers have enabled extraordinary advances in the understanding of geochemistry and hence past climate conditions on Mars. A similar understanding for Venus would be enabled by VME, so that a more complete view of the interconnected cycles of chemistry, volcanism, and climate on Venus would be obtained. This understanding is crucial for interpreting the spectral signatures and other data we would eventually obtain from terrestrial planets around other stars. The entire project, from new start to end-of-mission, could be accomplished in six to seven years, including a surface stay time of days or weeks.

The extreme temperature (~480°C); pressure (~90 bars) at the surface; and the highly-corrosive atmosphere at about 10 km above the surface of Venus present challenges for materials, mechanisms, and electronics. The surface conditions may also be potentially hazardous due to rough terrain, limiting surface access for sample collection. These technology challenges drive previous–decade technology investments and predicate this mission's new start upon a strategic technology decision point early in the decade. For further details, see the vignette on a Venus Mobile Explorer concept (see Vignette, Fig. 3-1).

3.2.4 Other Flagship Class Mission Concepts for Venus Exploration

Flagship missions beyond the 2015–2020 time frame will be defined and selected based upon the results of earlier missions. Examples of other high–priority Flagship class missions for Venus from the Decadal Survey and Roadmap, that would represent major scientific advances, include:

- A Venus Surface Sample Return (VSSR) mission, which would return a Venus surface sample to Earth for further analysis, in order to measure at high precision the isotopic composition of oxygen in surface rocks; and trace elements to characterize the age of rocks and characterize core-and-mantle formation. This mission would require significant technology development of sample acquisition and handling, including a multi-stage ascent air-mobility system to lift the sample to launch altitude. In orbit, rendezvous know-how could be inherited from the proposed Mars Sample Return mission.
- A Venus Geophysical Network mission that would investigate the internal structure and seismic activity of the planet; and in addition monitor the circulation of the atmosphere. It could also provide insight into the causes and effects of the apparent global-climate change that Venus experienced in the distant past. Key technologies for this long lived in-situ mission include high-temperature electronics for the telecom system; other telecom challenges to transmit high data volumes to Earth; radioisotope power systems with active cooling to all network elements; and highly efficient thermal-management and pressure-mitigation systems.

For further details on these Venus Surface Sample Return and Venus Geophysical Network concepts, see their respective vignettes (Fig. 3-1).

3.3 ESA Cosmic Vision—European Venus Explorer

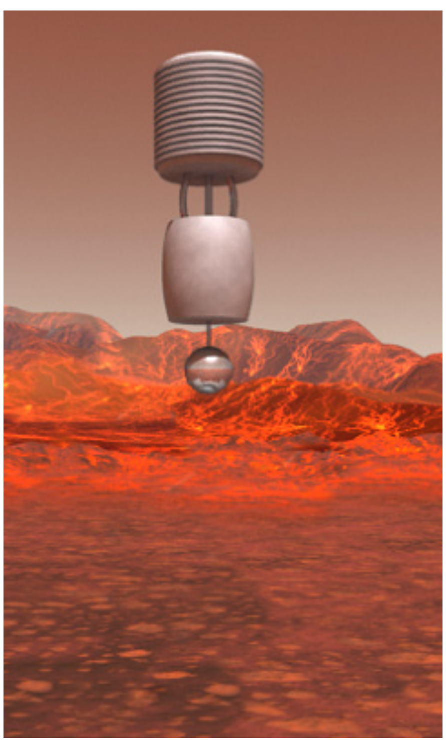
The European Venus Explorer (EVE) is a mission proposed to the European Space Agency (ESA), for launch in 2016–2018. While ESA's Venus Express mission is answering many questions about Venus, there are many questions which cannot be addressed by orbital measurements alone, in particular relating to the isotopic-ratio and cloud-chemistry objectives, issues which are the keys to understanding climate evolution on Venus. Consequently, the proposed EVE mission would focus on the evolution of Venus and its climate, with relevance to terrestrial planets everywhere. The EVE mission consists of one balloon platform floating at an altitude of 50–60 km; one descent probe provided by Russia; and an orbiter with a polar orbit, which would perform science observations as well as relay data from the balloon and descent probe. A lifetime of the balloon of 7 days enables one full transit around the planet. This is significantly longer than the 48 hours of data returned from Russia's VEGA balloons. Earth-based VLBI and Doppler measurements would provide tracking information for the orbiter, allowing measurement of the variations in the planet's gravity field, and for the balloon and descent probe to yield wind measurements in the lower atmosphere. The descent probe's fall through the atmosphere is expected to last 60 minutes, followed by a lifetime of 30 minutes on the surface. The Japanese space agency (JAXA) also proposes to include another independent platform, a small water-vapor-inflated balloon, which would be deployed at 35-km altitude and would communicate directly to Earth. Thus, the EVE mission is proposed as an international project, with participation from Europe, Russia, the USA, Japan and Canada.

3.3.1 Traceability of VEXAG Science Objectives against Proposed NASA Missions

In-situ missions to Venus would enhance our understanding and overall knowledge about the Solar System. Proposed missions must address four key interrelated areas:

- To be scientifically interesting,
- Programmatically affordable,
- Enabled by appropriate mission architectures, and
- Have the technologies necessary to achieve mission success.

Potential science returns from these proposed NASA missions are in a traceability matrix (see Table 3-2) where the missions are mapped against science objectives. Each Objective is grouped into one of three main VEXAG Goals, while the mission concepts are divided into Discover, New Frontiers, and Flagship classes. Green dots indicate that a mission can produce major contributions to meeting the science Objectives. Light-blue triangles show which missions can produce contributory science to these Objectives.



Artist's concept of a near-surface aerial platform. Using metallic bellows that provide buoyant support in Venus' dense lower atmosphere, this vehicle can explore vast regions of the surface at close range as it drifts with the near-surface winds.

Table 3-2. Traceability Matrix of Objectives Met with Discovery, New Frontiers, and Flagship Missions.

Mission Class	Discovery		New Frontiers	Flagship		
Objectives	**Venus Orbiter**	**High / Mid. Alt. Balloon**	**VISE**	**VME**	***VNET***	**VSSR**
Goal I. Origin and Early Evolution of Venus: How did Venus originate and evolve, including the lifetime and conditions of habitable environments in solar systems?						
Determine isotopic composition of the atmosphere		●	●	●		●
Map the mineralogy and composition of the surface on a planetary scale	▲	▲	▲	●		●
Characterize the history of volatiles in the interior, surface, and atmosphere	▲	▲	●	●		●
Characterize the surface stratigraphy of lowland regions and evidence for climate change	●	▲	●	●		▲
Determine the ages of various rock units on Venus			▲	▲		●
Goal II. Venus as a terrestrial planet: What are the processes that have and still shape the planet?						
Characterize and understand the radiative balance of the Venus atmosphere	●	●	▲	▲	▲	
Investigate the resurfacing history and the role of tectonism, volcanism, impact, erosion and weathering.	▲	▲	▲	●	▲	▲
Determine the chronology of volcanic activity and outgassing	▲		▲	●	▲	●
Determine the chronology of tectonic activity	▲			▲		
Investigate meteorological phenomena including waves, tides, clouds, lightning and precipitation.	●	●	▲	●	▲	▲
Goal III. What does Venus tell us about the fate of Earth's environment?						
Search for fossil evidence of past-climate change in the surface and atmospheric composition.		●	●	●		●
Search for evidence of changes in interior dynamics and its impact on climate	▲		▲	▲	●	▲
Characterize the Venus Greenhouse effect and its similarities to those on Earth and other planets	●	●	▲	▲	▲	
Convention: ● *Major Contribution* ▲ *Supporting Contributions*						
VISE – Venus In-Situ Explorer; VME – Venus Mobile Explorer; VNET – Venus Network Explorer; VSSR – Venus Surface Sample Return						

4. TECHNOLOGIES FOR FUTURE VENUS EXPLORATION

The success of future Venus missions depends on the capability to survive in the Venus environment. In-situ missions to Venus will encounter some of the most hostile environments in the Solar System. At Venus, the super-rotating atmosphere consists mainly of carbon dioxide (CO_2 ~96.5%) and nitrogen (N_2 ~3.5%), with small amounts of noble gases (e.g., He, Ne, Ar, Kr, Xe) and small amounts of reactive trace gases (e.g., SO_2, H_2O, CO, OCS, H_2S, HCl, SO, HF). The cloud layer is composed of aqueous sulfuric-acid droplets between the altitudes of ~45 and 70 km. The zonal winds near the surface are ~1 m/s, increasing up to ~120 m/s at an altitude of ~65 km. Due to the greenhouse effect, the surface temperature reaches 460°C to 480°C. The average surface pressure can be as high as ~92 bars. At these conditions near the surface, the CO_2 becomes supercritical, which could further complicate surface and near-surface missions. Under these supercritical conditions, electronics components and mechanical systems can fail due to alterations of materials by the environment. Therefore, mission-and-system architectures, and related technologies must address ways to mitigate these extreme-environmental conditions.

Although some Venus investigations can be accomplished from orbit using remote-sensing instruments, many key-science questions can only be answered by low-altitude and surface-in-situ-exploration of Venus. Short-duration missions that are expected to tolerate these environments for up to a few hours can be accomplished with currently available technologies. In comparison a Venus Mobile Explorer is expected to operate up to several months at or near the surface. Thus, architectures for future and their technologies must be able to mitigate these environmental conditions. Mitigations for these extreme environments will need:

- Isolation of sensitive materials from hazardous conditions,
- Materials that are tolerant to hazardous conditions, and
- Hybrid systems that have both isolation and tolerance.

For the hybrid systems, hardened components would be exposed directly to the environment while non-hardened components would be protected. For components inside a temperature-controlled enclosure, either passive or active cooling could be used. High-temperature-tolerant components are needed for in-situ sensors, drills, and sample-acquisition mechanisms, which would be exposed to the extreme environment. Thus, the temperature-sensitive components would be maintained inside an insulated-thermal enclosure, while the more tolerant components would remain outside.

Technologies can be categorized as heritage, enhancing, or enabling. Heritage technologies are those, which are flight qualified and do not need further development. Enhancing technologies are those, which would benefit a mission, but without them the mission could still be successful, although with reduced performance. Enabling technologies are those that make a mission possible. Enabling technologies are specifically required for accessing the surface of Venus as well as for exploring other extreme environments such as the deep atmosphere of Jupiter.

Success in accomplishing technology developments has a great influence in being able to conduct in-situ missions, whether they are entry probes, landers or aerial platforms. These technology developments are categorized as:

- Environmental-protection technologies providing isolation from extreme environments,
- Environmental tolerance for exposed components or systems, and
- Operations in extreme environments.

The first area includes technologies designed to protect spacecraft subsystems from the environment, including thermal protection systems (TPS) for hyper-velocity entry to mitigate extremely high peak-heat fluxes; as well as pressure and temperature control for the payload during in-situ operation. The second area includes technologies needed for developing tolerance to the harsh conditions through "component hardening," for items such as electronics, electro-mechanical systems, and energy storage. Today's commercially available high-temperature electronics can operate up to ~125°C, far below the requirements for the Venus environment. Development of temperature tolerance up to ~300°C, combined with a suitable thermal control would enable electronics to operate at or near the surface. The third area includes technologies for mobility and sample acquisition. Also, the environment will have an effect on telecommunication systems.

Systems architectures will influence which technology developments are needed. In-situ missions to Venus need technologies for high-temperature operations, including passive or active thermal cooling, pressure vessels, high-temperature electronics, energy storage, and high-temperature mechanisms. Venus landers with current technologies are limited to a few hours of operation. Short-duration, in-situ and probe missions can operate with passive-thermal control. Long-lived, near-surface missions will require active cooling to "refrigerate" the avionics and instruments, possibly powered by an internal-power source, such as an Advanced Stirling Radioisotope Generator. Improvements in pressure-vessel materials are needed to reduce mass, which then enables additional science instruments. High-temperature sample-acquisition systems will need environmental tolerance, since they interface directly with the environment.

Materials research will be important for aerial mobility, and parachute descent. For example, a Venus air-mobility platform employing metallic bellows would enable all axis control, long traverses and surface access to multiple locations. This would provide an advantage over static landers or rovers. A Venus air-mobility platform would enable missions for in-situ geological and geophysical investigations of Venus over substantial distances.

Specific technology developments for the different classes of Venus missions are listed in Table 4-1. Technologies are listed in the left-hand column by categories: such as transportation, power, communications, planetary protection, autonomy and software, entry, descent, and landing, planetary mobility, extreme environment technologies, remote sensing instruments, in-situ instruments, and component technology and miniaturization. Missions are listed in three classes: Discovery, New Frontiers, and Flagship, in the columns to the right. Green dots indicate which technologies are required for each mission. Open green circles indicate technological development that builds upon previous missions. Blue dots indicate needed technologies that have been retired by previous missions. Thus, a Discovery class mission such as a high- or

Table 4-1. Technology Requirements for Discovery, New Frontiers, and Flagship Missions.

Mission Class	Discovery		New Frontiers	Flagship		
Technologies	**Venus Orbiter**	**High / Mid. Alt. Balloon**	**VISE**	**VME**	**VNET**	**VSSR**
Spacecraft Systems Technologies						
Transportation						
→Access to Space						
→Solar-Electric Propulsion	●	▲				▲
→Aerocapture / Aeroassist		●		▲		▲
→Advanced-Chemical Propulsion				●		▲
Power						
→ Radioisotope (RPS)				▲	▲	
→ Solar Power		●				
→ Energy Storage		●	◉	◉	▲	▲
Communications						
→ Direct-to-Earth Communications		●	◉	▲	▲	▲
→ Proximity Links				●	▲	
Autonomy and Software						
→ Autonomous Systems	●	●	◉	◉	▲	▲
→ Software V&V				●	◉	▲
In-Situ Exploration Technologies						
Entry, Descent, and Landing						
→ Precision Navigation						
→ Hazard Avoidance				●	▲	▲
→ Small-Body Anchoring						

Mission Class	Discovery		New Frontiers	Flagship		
Technologies	**Venus Orbiter**	**High / Mid. Alt. Balloon**	**VISE**	**VME**	**VNET**	**VSSR**
Planetary Mobility						
→ Aerial		●	◉	◉		▲
→ Surface			●	◉		▲
→ Subsurface Access			●	◉		▲
Extreme Environment Technologies						
→ High Temperature / Pressure		●	●	◉	▲	▲
→ Low Temperature						
→ High Radiation						
→ High-Heat Flux – Entry System		●	●	◉	▲	▲
Science Instruments						
Remote-Sensing Instruments						
→ Active-Remote Sensing	●	●	●	◉		◉
→ Passive-Remote Sensing	●	●	●	◉		◉
In-Situ Instruments						
→ Analytical Instruments		●	●	●	●	◉
→ Sample Acquisition & Handling		●	●	◉		▲
Component Technology and Miniaturization						
→ Component Technologies		●	●	●	●	◉
→ Miniaturization		●	●	●	●	◉

Convention: ● *Technology Development Required* ◉ *Some Technology Development* ▲ *Risk Retired*

VISE – Venus In-Situ Explorer; VME – Venus Mobile Explorer;
VNET – Venus Network Explorer; VSSR – Venus Surface Sample Return

medium-altitude balloon will use technology developments in energy storage, direct-to-Earth communications and autonomous systems. These, in turn, will feed into a VISE mission. Thus, technology development feed forward of Discovery and New Frontiers missions will retire some of the technology developments for flagship missions.

Based on these considerations, priority should be given to the development of the key technologies that enable future exploration of Venus. Technologies listed in this section are preliminary and will be updated, based on the findings of a Flagship class mission study, planned for FY08.

Table 4-2. VEXAG-identified High-Priority Technology Development Needs (Summary of VEXAG Report of NASA Headquarters, December 2005)

For **short-duration** (hours to days) missions to Venus:
• Passive-cooling systems to enable survival of communications systems and instruments for measuring chemical, thermal, mechanical and physical (including seismic) properties at external temperatures of 470°C and pressures of 90 bars for periods of at least 1 Earth day. • High-temperature electronics for instruments and communication systems that will survive temperatures of up to 470°C for both short- and long-duration missions, so that cooling systems are not required for sustained-surface lifetimes. Electronic systems with lower-temperature tolerances are still desirable for passively cooled, short-duration missions, or for high-altitude missions (potentially 350–400°C). • Precision-landing capability, as many scientifically-interesting sites for landers have relatively modest-landing ellipses. • Autonomous hazard-avoidance systems to reduce risk for safely landing spacecraft. • Communications systems to handle large-data volumes (requiring potentially expanded capability in Earth-based receivers), and/or non-ideal landing sites (requiring potentially orbital-communications microsatellites). • For measurements of the chemical composition of rocks at a landing site, technology requirements include high-temperature extraction (potentially including drilling) and handling capability. • Geophysical electromagnetic-sounding techniques that can probe beneath the surface, obtaining constraints on crustal thickness and heat flow. • Planetary surface geochemical techniques and instruments such as X-ray diffraction, APXS, LIBS, and Raman spectroscopy. • In-situ age-dating techniques that can be applied to the hot rocks and soil of the Venus surface.
For **long-duration** (months to years) missions to Venus:
• Active cooling systems able to enable survival of scientific instruments and communication systems at external temperatures of 470°C and pressures of 90 bars for periods of at least 1 Earth year. Somewhat lower-temperature requirements of around 350–400°C would be required for high-altitude missions. • High-temperature power systems capable of providing power for instruments and communications with reduced requirements for active, cooling systems. • Long-lived balloons capable of operating from the near-surface (sufficiently close for use of optical/infrared sensors) to near the cloud deck (~50 km) for a combination of atmospheric measurements and observations/measurements of the surface (notably at frequencies not available to orbiting spacecraft). Tolerance to high temperatures (about 100–470°C), temperature excursions of several hundred degrees over periods of several hours, and potentially corrosive environments (notably near the cloud deck), for mission durations of an Earth week to an Earth month. • Seismometers capable of operation under Venus-surface conditions, with suitable communications systems. Sensitivity requirements are probably similar to Earth systems. Seismometers must be able to be suitably coupled physically to the solid planetary surface and must have a low aerodynamic profile in order to minimize wind-induced noise. Communications systems must be able to deal with relatively high-data-transfer rates; some rapid triggering of the data-recording system at pre-defined levels of ground motion would be necessary. • Heat-flow measurement capability for the Venus near surface, perhaps requiring emplacement of thermal sensors after drilling into the near surface below a lander. Requirements would include suitable-drilling technologies (may also be used for sample extraction for in-situ measurements of chemistry) and potentially high-temperature electronic systems.

5. FINDINGS AND PROPOSED ACTIONS

Key unanswered questions about Venus relevant to our understanding of the Earth as well as other terrestrial planet systems include:

- Was there ever an ocean on Venus, and if so, when did it exist and how did it disappear?,
- Was the early Venus atmosphere like the early atmosphere of Earth, and at what point did it diverge in character so greatly and why?,
- Why does Venus rotate so slowly and is the lack of a planetary dynamo a consequence? What was the impact on the evolution of Venus?,
- Why does Venus' atmosphere rotate 60-times faster than its solid body? How are atmospheric heat and momentum transferred from equator to poles?,
- What caused the extensive resurfacing of Venus during the last billion years? Is Venus still an active planet? Are the resurfacing and climate change somehow related?, and
- Was Venus ever habitable?

These questions and the recommendations of recent reports described in Section 1, VEXAG developed three overarching themes or goals:

- ***Origin and Early Evolution of Venus: How did Venus originate and evolve, including the lifetime and conditions of habitable environments in solar systems?,***
- ***Venus as a terrestrial planet: What are the processes that have shaped and still shape the planet?, and***
- ***Implications for Earth: What does Venus tell us about the fate of Earth's environment?***

With these questions in mind, objectives, investigations, and the needed technologies to accomplish the identified top priority items have been outlined. The result is in effect a science-traceability matrix for future exploration and research, and also for related technology developments given as tables in Sections 3 and 4.

As a planetary exploration target, Venus presents us with especially challenging hurdles, including its cloud cover that obscures the surface from conventional imagers and its inhospitable lower atmosphere and surface environments. Consequently, meaningful answers to many of the above questions require the development and validation of significant technical innovations. Thus, the technological investments are important as they represent steps that need to be taken as early as is feasible to enable the needed measurements. They also need to be considered in the near term assuming a Venus In-Situ Explorer (VISE) mission remains part of the list of solicited New Frontiers missions in the next announcement of opportunity for that mission line, subject to the current review of mission candidates by COMPLEX.

VEXAG discussions and deliberations to date, together with the Venus goals, objectives, and investigations documented above, lead to the following overall findings and proposed actions toward addressing the next steps toward Venus exploration:

5.1 Venus Science

After a two-decade hiatus, the Venus community is now acquiring important new information on the surface, atmosphere, and solar-wind interaction of Venus. For example, in one year of operation at Venus, the ESA Venus Express (VEX) orbiter has obtained observations relevant to the search for active volcanism, lightning, and atmosphere-escape rates. On June 5, 2007, the Discovery Messenger mission performed an encounter with Venus and acquired laser-altimeter as well as X-ray and infrared-emission spectrometer data. These data will be placed in the Planetary Data System (PDS) within 6 months. Other Venus Express observations will also soon be added to the PDS. However the involvement of U.S. scientists in Venus Express data analysis is currently limited to a few Participating Scientists, Interdisciplinary Scientists, and Support Investigators, who only cover a small range of areas of scientific interest.

Finding: Without additional resources, the US Venus science community will fall further behind in leadership in Venus exploration. There will be no opportunity to fully take advantage of the results of either the VEX mission or the Messenger flyby in our future plans for Venus exploration, or to train the next generation of Venus scientists.

Proposed Action: In order to fully exploit the results from both the Venus Express and Messenger at Venus, made available via the PDS, funds should be identified to enable **a**mending of the NASA Research Announcement (NRA) to include a Venus Data Analysis Program open to all.

5.2 Venus Flagship Mission

The Solar System Roadmap has identified a program of Flagship missions to address key scientific questions that cannot be solved with small and moderate missions. A Venus Flagship mission is included in the three highest priority missions (Europa Explorer, Titan-Enceladus Explorer and Venus Mobile Explorer). The Roadmap also notes that the Venus Flagship requires new technologies and complex systems to cope with the searing heat and intense pressure of the Venus lower atmosphere and surface. NASA has recently initiated studies of Flagship Missions to Europa, Titan and Enceladus but no study of a Venus flagship mission has yet been initiated.

Finding: The completion by VEXAG of scientific goals and priorities now makes it timely to initiate a study of the Flagship mission in other to define a concept in more detail, and identify the technologies needed to implement the mission. This study should not be delayed because a path to addressing specific technology challenges that the resulting mission concept raises must be embarked upon at the earliest opportunity.

Proposed Action: The Planetary Science Division should initiate a study of a Flagship mission to Venus at the earliest opportunity**.** The study should assess:

- Key scientific questions that can be addressed by a long-duration mobile mission to the surface or near surface of Venus,
- Alternative missions architectures for addressing these scientific questions,
- Precursor scientific measurements and technology validation that might be implemented with prior Discovery and New Frontiers missions, and

- Technology investments needed to enable the Venus Flagship mission, emphasizing the long-lead time technologies needing early investment.

5.3 Venus New Frontiers Mission

The NRC Solar System Decadal Survey recommended Venus In-Situ Explorer (VISE) as one of four New Frontiers mission candidates. The strawman mission proposed by the Decadal Survey acquired a surface sample and raised it with a balloon to Venus' middle atmosphere for remote analysis. This mission would thus have served as the precursor for a Venus Surface Sample Return that would also transfer a sample to the middle atmosphere but then launch the sample to space. The 2003 New Frontiers AO noted that, "*any mission architecture that achieves the majority of the science objectives stated above for a cost within the New Frontiers cost cap will be considered responsive to this AO.*" However, no proposal for VISE was selected to proceed to Step 2 in 2003.

Finding: VEXAG considers that the Venus In-Situ Explorer (VISE) continues to be a vital mission in the exploration of Venus and should be included in the FY08 New Frontiers AO. The scientific goals stipulated in the FY03 New Frontiers AO remain valid. In addition to its scientific value, the VISE mission offers a unique opportunity to validate capabilities that would be important to a future Flagship mission.

Proposed Action: The Venus In-Situ Explorer (VISE) should be included in the New Frontiers AO for 2008 and the general scientific goals for this mission should remain unchanged. NASA should consider implementing a technology-validation element to VISE in particular that would permit demonstration of technologies needed for a long-duration mobile mission but not necessary to the success of VISE itself.

5.4 Technology Investments

Just as the solution to many high-priority scientific questions about Mars required landed and mobile in-situ exploration of the surface, major advances in Venus science will eventually require in-situ surface measurements. The impediment has been the technical difficulty of operating at the extreme pressures and particularly at the very high temperatures near and on the Venus' surface. There are opportunities to leverage technologies developed for operation in similar environments encountered in aerospace (jet and rocket engine) and deep drilling applications. Nevertheless, the conditions at the surface of Venus are unique with hot, supercritical carbon dioxide representing a significant challenge for operations. Many other considerations related to the environment are unknown due to the lack of adequate environmental-simulation chambers.

Findings: There are credible technical approaches, leveraging from technologies developed in industry to achieving extended operation in the Venus environment. High-temperature electronics can enable systems to operate for extended periods. Advanced radioisotope-power systems and active thermal-control systems could enable conventional components such as microprocessors or imaging sensors to operate for extended periods on the surface of Venus. While further work on mission architectures will be needed to define specific-performance goals and focus the technology, work on the technology can and should begin now. Without NASA direct involvement, it will not be possible to apply the results from industry to the specific needs of in-situ and near-surface exploration.

Proposed Action: NASA should initiate a program to develop technologies for operation in the extreme environment of Venus. These should include:

- Passive thermal-control technologies for extending the period of operation on or near the surface from hours to days,
- Active thermal control technologies and power generation systems for extending the period of operation in the Venus environment to many months,
- High temperature electronics and other components capable of extended operation directly exposed to the Venus surface environment,
- Mobility systems for operation at the surface and in the lower atmosphere of Venus, and
- A program of systems analyses to establish performance objectives and evaluate alternative approaches for mission architectures.

If funds were available, this could be competed through an amendment to the ROSES NRA, perhaps as part of a larger extreme-environments technologies initiative.

5.5 Venus as a Future Earth

Several VEXAG participants noted the potential role for the study of the Venus greenhouse effect in better understanding Earth's climate stability and change. In general there is much to be learned about both our own planet and extrasolar-terrestrial planets from the divergent paths of Earth and Venus over time. Will the warming Earth ultimately become a Venus?

Finding: A useful dialogue between Venus and Earth scientists is lacking.

Proposed Action: A research program, encouraging conferences and/or workshops, should be initiated that brings together Earth and Venus scientists for a focused study of the evolutionary aspects (past and future) of these terrestrial-planet twins. Areas of mutual interest could include extreme-climate scenarios, and/or the role of volcanism, tectonics, and the presence/absence of a planetary dynamo in determining the fate of a planet and its atmosphere.

VEXAG strongly suggests that these proposed actions be enacted immediately. Furthermore, VEXAG strongly endorses progress toward the definition of flagship mission concepts under a separately appointed NASA Science Definition Team (SDT) to be formed in the coming year.

6. REFERENCES

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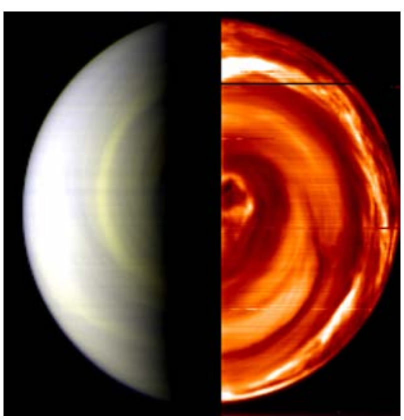
7. ACRONYMS AND ABBREVIATIONS

AO	Announce of Opportunity
ASPERA	Analyzer of Space Plasmas and Energetic Atoms
ASRG	Advanced Stirling Radioisotope Generator
COMPLEX	Committee on Planetary and Lunar Exploration
DSN	Deep Space Network
ESA	European Space Agency
EUV	Extreme Ultra-violet
EVE	European Venus Explorer (Cosmic Vision proposal, 2007)
GC/MS	Gas chromatograph / mass spectrometer
JAXA	Japanese Aerospace Exploration Agency
MAG	Magnetometer (experiment on Venus Express)
MEPAG	Mars Exploration Program Analysis Group

MER	Mars Exploration Rovers
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging (mission)
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NF	New Frontiers
NRA	NASA Research Announcement
NRC	National Research Council
PDS	Planetary Data System
POV	Pioneer Venus Orbiter
R&A	Research & Analysis
RADAR	K-band SAR on the Cassini spacecraft
SAR	Synthetic aperture radar
SOIR	Solar Infrared Spectrometer augmentation to SPICAV
SPICAV	Spectroscopic Investigation of the Characteristics of the Atmosphere of Venus (experiment on Venus Express)
SSE	Solar System Exploration
SDT	Science Definition Team
TPS	Thermal protection systems
USSR	Union of Socialist Soviet Republics
VCO	Venus Climate Orbiter
VDAP	Venus Data Analysis Programs
VEGA	Russian Halley/Venus Lander and Orbiter Mission
VEPAG	Venus Exploration Program Analysis Group
VeRa	Venus Radio (experiment on Venus Express)
VESPER	Proposed NASA Discovery mission
VEX	Venus Express
VEXAG	Venus Exploration Analysis Group
VIMS	Visual and Infrared Mapping Spectrometer
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer
VISE	Venus In-Situ Explorer
VLBA	Very-Long Base Array
VMC	Venus Monitoring Camera
VME	Venus Mobile Explorer



Venus' dynamic south-polar meteorology as revealed in 3-D by the VIRTIS spectral imager on Venus Express. The daylight side of the planet is shown in the left; the nighttime hemisphere on the right. In daylight, the UV portion of VIRTIS' spectral complement images the uppermost haze layers near the 70-km level. In the nighttime imagery, VIRTIS images an entirely different regime of clouds and meteorology near the 50-km level. Seen in silhouette against Venus' thermal glow generated by the oven-hot atmosphere below, these variable clouds of sulfuric acid swirl around the pole in a hurricane-like fashion (courtesy of ESA).