The Venus Science and Technology Definition Team Flagship Mission Study

A White Paper for the Planetary Sciences Decadal Survey

September 15, 2009

Mark A. Bullock, Southwest Research Institute, Boulder, Colorado
(bullock@boulder.swri.edu)
David A. Senske, Jet Propulsion Laboratory
Tibor. S. Balint, Jet Propulsion Laboratory
Alexis Benz, Jet Propulsion Laboratory
Bruce A. Campbell, Smithsonian Institution
Eric Chassefiere, Service d'Aéronomie, France
Anthony Colaprete, NASA Ames Research Center
James A. Cutts, Jet Propulsion Laboratory
Lori Glaze, NASA Goddard Space Flight Center
Stephen Gorevan, Honeybee Robotics
David H. Grinspoon, Denver Museum of Nature & Science
Jeff Hall, Jet Propulsion Laboratory
George L. Hashimoto, Okayama University, Japan
James W. Head, Brown University
Gary Hunter, NASA Glenn Research Center
Natasha Johnson, NASA Goddard Space Flight Center
Viktor V. Kerzhanovich, Jet Propulsion Laboratory
Walter S. Kiefer, Lunar and Planetary Institute
Elizabeth A. Kolawa, Jet Propulsion Laboratory
Tibor Kremic, NASA Goddard Space Flight Center
Johnny Kwok, Jet Propulsion Laboratory
Sanjay S. Limaye, University of Wisconsin
Stephen J. Mackwell, Lunar and Planetary Institute
Mikhail Y. Marov, Vernadsky Institute, Russian Federation
Adriana Ocampo, NASA Headquarters NASA Headquarters
Gerald Schubert, University of California
Ellen R. Stofan, Proxemy Research
Hakan Svedhem, European Space Agency, Netherlands
Dimitri V. Titov, Max Planck Institute, Germany
Allen H. Treiman, Lunar and Planetary Institute

Venus Science Goals and Objectives

There is a compelling motivation of great global concern for exploring Venus: As we discover how climate and geology work on a world similar to our own, we gain a deeper understanding of the processes at work in our own environment. With the realization that the Earth's climate system is not sufficiently well understood, and the threat of accelerating anthropogenic changes to the atmosphere, comes a valid concern about the natural vulnerability of the world in which we have thrived. What are the limits of stability of the global system under the influence of human consumption and effluent? Could rapid or irreversible changes be triggered by the current unprecedented pace of greenhouse gas input to the atmosphere (Solomon et al., 2007)? Are there climate tipping points beyond which there is no return? To this last question, because of planetary exploration, we know the answer. Yes. Venus' oceans boiled away in a dramatic runaway greenhouse and were eventually lost to space. If this happened to Venus, could it happen to Earth? Again, the answer is yes. Earth will someday pass the tipping point, its oceans will boil, and a desiccated, hot Earth will be like Venus today. We know this because main sequence stars like the Sun slowly increase in luminosity as their fuel is used up. Subtler discontinuities in climate, with real consequences for society, are certainly possible and climate feedbacks that might be difficult to discern in the Earth system might be illuminated by the deeper understanding of planetary climate gained by studying the climate of Venus.

Our great progress in exploring Mars illustrates how in-depth exploration of a nearby terrestrial planet can successfully illuminate Earth processes. Mars's dynamic surface, accessible to our eyes for centuries and comparatively benign as an environment for spacecraft exploration, has revealed how physics and chemistry have shaped another rocky world. This cold, dry planet has a history of water, climate, and potential habitability starkly different from our own. Other planets will, of course, offer radically different comparisons. Venus, too, we believe, had early oceans but lost this habitable environment for completely different reasons. Verifying and quantifying this story will immensely improve our understanding of how Earth-like worlds come to be and how they might evolve to either encourage life or extinguish it. More immediately, the nature of climate feedbacks that might ultimately determine the physical safety and economic security of society must be understood. Some of the most revealing secrets to the formation of the solar system, the evolution of climate on our own planet, and the habitability of terrestrial planets around other stars can be found only on Venus. But the searching is difficult: Venus' obscuring cloud layer and hostile environment have made it a challenging planet to explore. Nevertheless, many of the scientific investigations that should be done to understand the Venus system and relate those results to our own world can be achieved by a flagship mission to Venus. This white paper 1) describes in detail the important science that should be done at Venus in the coming decades to achieve these goals and 2) details a flagship Design Reference Mission (DRM) to accomplish many of them.

The noble gas ratios in planetary atmospheres tell the story of early loss, whether by giant impacts or EUV powered hydrodynamic escape. How likely and how catastrophic can atmospheric loss events be on terrestrial planets, and can they inhibit the origin of life or set the stage for sustained habitability? The Earth seems to have lost most of its original Xe, indicating the catastrophic loss of an early atmosphere. The noble gases in Venus' atmosphere have never been measured with sufficient precision to deduce its early evolution.

The lowest scale height, in which 67% of the atmosphere resides, has never been chemically measured. Above these altitudes, strong gradients in CO, OCS, and SO_2 have been observed.

Although it is likely that atmospheric chemistry is involved in creating most of these gradients, vigorous reactions with the surface as a source or sink of gases is also a strong possibility. How these gases have reacted with surface rocks, believed to be mostly mafic and alkaline basalts, is of intense interest. Sulfur is expected to weather basalts and react with carbonates, yielding a unique assemblage of alteration products. These products and their distributions hold the key to understanding recent changes in atmospheric composition and climate. The large portion of the surface that has been volcanically resurfaced over the last billion years, combined with models of climate change due to volcanically generated gasses and cloud particles, suggest that global change on Venus may depend on complex feedbacks between geological and atmospheric evolution. Radically different as the surface environments of Venus and Earth are, it is the study of the interconnections of these processes that will yield inevitable benefits for understanding the Earth's complex climate system

The bulk of the atmosphere of Venus faster than its solid body with many layers at the equator moving faster by as much as 60 times the surface. The atmosphere has fully 0.15% of the angular momentum of the planet. Jets and waves are seen at all levels in the clouds, but the below-cloud atmosphere, which may experience baroclinic storms or barotropic eddies, has not been explored. The thermally direct Hadley cell circulation transports angular momentum polewards thereby creating a mid-latitude jet at the observerd cloud level. The equatorial regions in the cloud level must be replenished with angular momentum somehow. Although it has not been directly observed, a return flow in the deep atmosphere is required. It has been suggested that thermal tides and eddy motions might accomplish this, but we have been flummoxed at confirming this for lack of adequate observations and even unable to simulate it with the fastest supercomputers. With such a dramatically different meteorology, it might be expected that little could be learned from studying the maelstrom that is Venus' atmosphere. Yet the ways that angular momentum and heat are transferred in the Earth's atmosphere represent some of the most important areas of current research and important for our basic understanding of our own climate. It is important that we understand the puzzling circulation on a planet with far simpler physical attrtibutes than our own. The role of clouds in visible and thermal radiation, and their coupling to radiation and dynamics are processes that are poorly understood on both Earth and Venus. Venus' exaggerated dynamics promise to elucidate subtle aspects of the Earth's circulation and their feedbacks,

The greenhouse effect on Venus is strong almost beyond our imagination – carbon dioxide is in such abundance that it is like a global ocean that absorbs virtually all of the thermal radiation, producing an average surface temperature over 455°C. The term 'runaway greenhouse' was originally dubbed to describe the state of Venus' climate (Ingersoll, 1969), but it has also been ominously applied to extreme anthropogenic climate change on the Earth (Hansen, 2008). The physical and chemical connections that drive greenhouse climate change cannot help but be much better understood by thoroughly exploring Venus.

Why is Venus so different from Earth? The science driving a flagship-class mission to Venus can be summarized by its three themes:

1. What does the Venus greenhouse tell us about climate change? The Venus greenhouse is poorly understood because it is coupled to the still mysterious atmospheric dynamics and cloud physics. To better understand the atmosphere, experiments that simultaneously probe dynamics, chemical cycles, energy balance, and isotopic abundances must be performed, mostly *in situ*.

2. How active is Venus? The search for Venus' activity ranges from detecting active volcanic processes, to tracking the clouds and analyzing meteorological data such as the winds, pressures, and temperatures. Detecting ground movement at one location and monitoring the planet globally for seismic events are the most definitive tests for internal structure and activity.
3. When and where did the surface water go? Mineralogical and chemical analyses of Venus' surface, if done with sufficient precision, have the potential to revolutionize our understanding of Venus' geology. The ability to analyze both rocks and soils and to drill to depths within pristine rocks holds the key to past changes in atmospheric conditions, volcanism, and climate. Volcanism, tectonism, and weathering affect the climate of Earth in profound ways.

The top-level science objectives for a Venus flagship mission can be traced directly from these three science themes in Table 1.

Table 1. Top-Level Science Themes and Objectives for the Venus Flagship Mission.

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

Science and Technology Approach

The Venus Science and Technology Definition Team was created by NASA's Science Mission Directorate to formulate the science goals and objectives and to design the mission architecture, science investigations, and instrument payload for a flagship-class mission to Venus. It was also tasked with developing a prioritized technology roadmap to bring the necessary technologies and instruments to sufficient technology readiness levels. This was facilitated by a JPL engineering study team and JPL's Advanced Projects Design Team (Team X). This $3- to $4-B flagship mission, to launch in the 2020 - 2025 timeframe, should revolutionize our understanding of how climate works on terrestrial planets, including the close relationship between volcanism, tectonism, interiors, and atmospheres.

The work of the STDT was divided into two phases. Phase 1 was a very broad look at the science objectives for a Venus flagship mission and a detailed consideration of a large range of mission architecture options. The STDT drew upon the successful multi-year community Venus Exploration and Analysis Group (VEXAG) effort to define the science goals and objectives for the exploration of Venus (VEXAG, 2007), as well as the NRC Solar System Decadal Survey (National Research Council, 2003) and its update (National Research Council, 2008) and the 2006 NASA Roadmap (NASA, 2006). Phase 2 focused on creating a flagship-class Design Reference Mission that would provide optimal science return for a detailed exploration of Venus.

This point design provides preliminary estimates of the mass, power, data, and cost resources needed for a flagship mission to Venus, along with a set of technology development requirements. The team also studied science and technology enhancements to the flagship mission that could be done if, for example, one or more smaller missions advances knowledge of Venus before the flagship is flown.

The Venus Flagship Design Reference Mission

The Venus Flagship Design Reference Mission, optimized to achieve the most high-priority science, is comprised of a highly capable orbiter, two balloons in the clouds, and two landers on different terrains. The orbiter provides telecommunication relay support for a month-long balloon campaign and two five-hour landers and then aerobrakes into a 230-km circular science mapping orbit for a two-year mapping mission. Extremely high-resolution radar and altimetry mapping will explore the surface at resolutions up to two orders of magnitude greater than was achieved with Magellan, opening a new door to studies of comparative geology. While the balloons circumnavigate the planet up to seven times, they continually sample gases and cloud aerosols and measure the solar and thermal radiation within the clouds. The landers perform descent science, obtaining atmospheric measurements in complementary vertical slices and taking images of the surface on the way down. While on the surface, they perform high-fidelity analyses of the elemental and mineralogical content of rocks and soils on and beneath the surface. Panoramic images of the landing sites at an order of magnitude higher resolution than achieved with previous landers provide geologic context for the landing and sampling sites. The mission requires two Atlas V 551 launch vehicles in the 2020 - 2025 timeframe: one for the orbiter, the other for the in situ vehicles and carrier. The preliminary cost analysis for the DRM gives a range of $2.7 B to $3.8 B in $FY09.

Clearly, the technological challenges for in situ exploration of Venus are high. The STDT considered mission architectures and payloads whose components and instruments could be at Technical Readiness Level (TRL) 6 or higher by 2015. This ruled out a large number of scientifically promising approaches. Therefore, beyond the DRM, we considered the extra capabilities of a slightly enhanced mission that could be accommodated with the DRM architecture and entirely new capabilities for different architectures that would require a moderate, sustained technology program to achieve extraordinary science return from Venus. Table 2 shows how the major open questions defined by the STDT can be addressed by the DRM, by enhancements to the DRM, and by new capabilities for different architectures.

The DRM accomplishes a very wide range of atmospheric, geologic, and geochemical investigations to illuminate how the atmosphere, clouds, surface, and interior interact over many timescales. It does this by using the synergy of simultaneous atmospheric and surface in situ exploration under a very capable mapping orbiter. The total science performance of the DRM is shown in the 4th colored column, ‘DRM with synergies.’ The answer to whether Venus ever lost a primary atmosphere through impacts or massive escape will be obtained definitively. Investigations into the structure and evolution of the interior are not as well represented. On the right side, under ‘New Capabilities,’ it is apparent that a seismometry network will be required to answer these important geophysical questions about Venus.

As shown in the middle set of colored columns, enhancements to the DRM that are easily achievable by 2015 with an appropriate technology program can greatly improve the science return of the Venus flagship mission. What is not shown is that these enhancements also reduce risk.

Table 2. Major Open Questions and How the DRM and Capabilities Beyond Can Address Them.

MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS	DESIGN REFERENCE MISSION				DRM ENHANCEMENTS				NEW CAPABILITIES			
	Orbiter	Landers	Balloons	DRM with synergies	Orbiter	Landers	Balloons	with synergies	Seismic/ Meteor Stations	Low Alt Balloon	Long Duration Lander	Drop Sondes/ Lidar
VENUS ATMOSPHERE												
How did Venus evolve to become so different from Earth?	Yellow	Green	Orange	Green	Yellow	Green	Orange	Green	Yellow	Orange	Green	Orange
Was Venus ever habitable, and for how long?	Yellow	Green	Orange	Green	Yellow	Green	Orange	Green	Yellow	Orange	Green	Orange
Did Venus lose a primary atmosphere due to impacts or loss to space?	Orange	Blue	Blue	Blue	Orange	Blue	Blue	Blue	Orange	Blue	Blue	Blue
What drives Venus' atmospheric superrotation?	Green	Yellow	Green	Green	Green	Yellow	Green	Blue	Yellow	Green	Yellow	Green
How do geologic activity and chemical cycles affect the clouds and climate?	Yellow	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Yellow
How are atmospheric gases lost to space?	Green	Yellow	Yellow	Green	Green	Yellow	Yellow	Green	Orange	Orange	Yellow	Yellow
VENUS GEOLOGY												
What is the volcanic and tectonic resurfacing history of Venus?	Green	Green	Yellow	Green	Green	Green	Yellow	Blue	Green	Green	Green	Yellow
How were the heavily deformed highlands made?	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Green	Yellow	Green	Yellow
How active is Venus geologically?	Green	Green	Yellow	Green	Green	Green	Yellow	Green	Blue	Blue	Green	Yellow
Did Venus ever have plate tectonics and if so, when did it cease?	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Yellow
How are geology and climate connected on Venus?	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Green	Green
What has been the role of water and other volatiles in Venus geology?	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Yellow	Green	Yellow
VENUS INTERIOR STRUCTURE												
Does Venus have Earth-like continents?	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Blue	Blue	Green	Blue	Yellow
What are the chemical, physical, and thermal conditions of the interior?	Yellow	Yellow	Orange	Green	Yellow	Yellow	Orange	Green	Green	Orange	Green	Yellow
How does mantle convection work on Venus?	Yellow	Yellow	Orange	Yellow	Yellow	Yellow	Orange	Yellow	Green	Yellow	Green	Orange
What is the size and physical state of the core?	Yellow	Yellow	Orange	Yellow	Yellow	Yellow	Orange	Yellow	Blue	Orange	Blue	Orange
What is the structure of the Venus lithosphere?	Yellow	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Blue	Yellow	Blue	Yellow
How have water and other volatiles affected Venus' interior evolution?	Yellow	Yellow	Yellow	Green	Yellow	Green	Yellow	Green	Green	Yellow	Green	Yellow
VENUS GEOCHEMISTRY												
Was there ever an ocean on Venus, and if so, when and how did it disappear?	Yellow	Green	Orange	Green	Yellow	Green	Orange	Green	Yellow	Yellow	Green	Yellow
What caused the resufacing of Venus over the past billion years?	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green	Green	Yellow
What is the nature of chemical interactions between surface and atmosphere?	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Orange	Yellow	Green	Green
What are the tectonic forces behind Venus' volcanism?	Yellow	Yellow	Yellow	Green	Green	Yellow	Yellow	Green	Green	Green	Green	Yellow
How were the rocks and soils of Venus formed?	Yellow	Green	Orange	Green	Yellow	Green	Orange	Green	Yellow	Yellow	Green	Yellow
What do chemical differences of terrains say about the evolution of Venus?	Yellow	Green	Yellow	Green	Yellow	Green	Yellow	Green	Orange	Yellow	Green	Yellow

Blue	Fully addresses question
Green	Major progress in answering the question
Yellow	Partial answer to the questions
Orange	Will not answer the questions

To summarize, the Venus Flagship Design Reference Mission consists of:

- Dual Atlas V launches, one with the orbiter and one with the in situ package
- Dual Type II/IV launch trajectories to Venus available in 2021, 2023 and 2024.
- A highly capable orbiter with aerobraking capabilities to achieve a science mapping orbit
- 2 highly instrumented balloons floating within the Venus clouds for up to a month
- 2 capable descent vehicles/landers with the ability to analyze the chemistry, geology, mineralogy, and elemental composition of their landing sites, with 1 hour of descent science and 5 hours on the surface

A high-level traceability matrix for the Venus DRM that shows how each science theme flows to science objectives, investigations, and observation platform (i.e. orbiter, balloons, and landers) is presented in Table 3. The complete final report of the Venus Science and Technology Definition Team and supporting documents can be found at http://vfm.jpl.nasa.gov/

Table 3. Traceability from science themes, to objectives, instruments and platforms.

Science Theme	Science Objective	Instrument type	Observation Platform
What Does the Venus Greenhouse tell us about Climate Change?	Characterize the dynamics, chemical cycles, and radiative balance of the Venus atmsphere	Vis-NIR Imaging Spectrometer	Orbiter
		Sub-millimeter sounder	Orbiter
		Langmuir probe	Orbiter
		Atmospheric Structure (P/T/winds/accel)	Balloon, Lander (on descent)
		Nephelometer	Balloon, Lander (on descent)
		Net Flux Radiometer	Lander (on descent)
		Radio (with USO)	Balloon
	Place constraints on the evolution of the Venus atmosphere	Neutral and Ion Mass Spectrometer (INMS)	Orbiter
		GC/MS	Balloon, Lander (on descent)
How Active is Venus?	Identify evidence of active tectonism and volcanism and place constraints on evolution of tectonic and volcanic styles	InSAR	Orbiter
		Radio (with USO)	Orbiter
	Characterize the structure and dynamics of the interior and place constraints on resurfacing	Magnetometer	Orbiter, Balloon, Lander
		Heat flux plate	Lander
		Seismometer	Lander
	Place constraints on stratigraphy, resurfacing and other geologic processes	Vis-NIR camera	Balloon, Lander (on descent)
When and where did the water go?	Identify evidence of past environmental conditions, including oceans	GC/MS	Balloon, Lander (on descent)
	Characterize geologic units in terms of chemical and mineralogical composition of the surface rocks in context of past and current environmental conditions	Microscopic Imager	Lander
		XRD/XRF	Lander
		Passive Gamma-ray detector	Lander
		Drill and sample acquisition, transfer and preparation	Lander

Recommended Technology Development

The Venus STDT developed a prioritized set of technological challenges that must be met to bring all instruments and spacecraft systems to a Technological Readiness Level of 6 by 2016. In addition, the STDT studied more advanced technologies that could enable greatly enhanced science and pave the way for an eventual Venus Surface Sample Return (VSSR) mission. Key to enabling a Venus flagship mission is the ability to conduct investigations and tests in Venus simulation chambers. Table 4 shows recommended technology development for Venus exploration in priority order. Further details on technologies that enable or enhance future missions can be found in the Venus technology white paper, submitted to the NRC.

Conclusion

A flagship-class mission to Venus is NASA's first opportunity to fly a large mission to another Earth-sized planet with the explicit intention of better understanding our own. A deep understanding of how atmospheric greenhouses work, how volcanic and tectonic processes operate on a planet without plate tectonics, and the fate of oceans on terrestrial planets is within reach. The flagship mission described in this report represents an armada of interconnected platforms to explore the Venus atmosphere and surface in a way that will cast new light on our home world.

Table 4. Venus Exploration Technology Development Priorities.

	Technologies for DRM	Comments
1	Surface sample acquisition system at high temperature and pressure conditions	Drilling, sample collection and sample handling are enabling for the Design Reference Mission. Heritage Soviet-derived systems are not available off the shelf, but they demonstrate a feasible approach.
2	Lander technologies for rotating pressure vessel and rugged terrain survivability	Rotating pressure vessel concept is powerful but technologically immature. Tessera and other rugged areas on Venus cannot be reliably accessed unless a properly engineered rugged terrain landing system is provided.
3	Venus-like environmental test chamber	This capability is critical for testing and validation of science measurements as well as for testing of components and systems for their survivability in Venus environment
	New Capabilities	Comments
4	Refrigeration for the Venus surface environment	Almost every long duration (beyond 25 hrs), in situ platform will require some amount of refrigeration to survive. Focus should be on radioisotope-based duplex systems that produce both refrigeration and electrical power.
5	High temperature sensors and electronics, including telecom systems	Refrigeration requirements can be drastically reduced if electronics can operate at elevated temperatures. While a Venus ambient 460°C capability would be most desirable for telecom, data processing/storage, and power electronics, a major reduction in refrigeration loads could be realized already with moderate temperature operation (> 250° C).
	Enhancement to Current DRM Design	Comments
6	Extension of lander life through advanced thermal control	Human intervention during the landers operation on the surface of Venus is not possible unless landers life is extended to at least 24 hrs.

References

Ingersoll, A. P., 1969. The runaway greenhouse: A history of water on Venus. Journal of the Atmospheric Sciences. 26, 1191-1198.

NASA, Solar System Exploration Roadmap. Washington, DC, 2006, pp. 154.

National Research Council, 2003. New Frontiers in the Solar System: An Integrated Exploration Strategy. The National Academy Press, Washington, D.C.

National Research Council, 2008. Committee on New Opportunities in Solar System Exploration: An Evaluation of the New Frontiers Announcement of Opportunity. The National Academies Press, Washington, D.C.

Solomon, S., D., Q., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. Eds.), 2007. Climate Change 2007: The physical science basis - Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

VEXAG 2007. Venus scientific goals, objectives, investigations, and priorities: 2007, eds J. Luhmann and S. Atreya.