

An aerial photograph of a mountain range with a river valley. The mountains are rugged and brownish, with a river winding through the valley below. The sky is a pale, hazy blue.

VEXAG

Venus Science Goals, Objectives, and Investigations, and New Frontiers Mission Concepts

Inner Planets Panel Meeting 1

Sue Smrekar, Sanjay Lamaye, & Executive Committee

Aug. 27, 2009

Outline

- VEXAG Intro
- White papers in work
- Why Venus? Why now?
- Science Themes
- VEXAG Goals, Objectives, Investigations w/science questions
- New Frontiers Missions Concepts
- Future VEXAG Activities

Intro to VEXAG

- VEXAG initiated in 2003; past chairs: Janet Luhmann, Sushil Atreya, Ellen Stofan
- *Co-chairs:* Sanjay Limaye and Sue Smrekar recently appointed
- *Executive Committee:* Mark Allen, Kevin Baines, Jim Cutts, David Grinspoon, Lori Glaze, Adrianna Ocampo, with Tibor Balint, Mark Bullock, Larry Esposito, Jim Garvin, Ronna Hurd, Natasha Johnson, David Senske, Tommy Thompson, Allan Trieman
- Developing Decadal Survey inputs:
 - White Papers
 - Mission Concepts
- International Venus exploration activities identified
- Comparative Planetology – AGU Fall Meeting Session in 2008
- ESLAB Conference on Venus-Earth-Mars in May 2009 (at ESTEC)

Decadal Survey Inputs: White Papers

White Paper Topic	Lead(s)	Status
Venus Exploration Goals, Objectives, Investigations, and Priorities	Sanjay Limaye & Sue Smrekar	Completed
Technologies for Venus Exploration	Jim Cutts and Tibor Balint	Completed
Venus Atmosphere	S. Limaye with K. Baines, C. Covey, K. McGouldrick, G. Schubert É.	In progress
Comparative Climatology of Venus, Earth, and Mars	David Grinspoon & Mark Bullock	In progress
Venus Geochemistry: Progress, Prospects, and Future Missions	Allan H. Treiman, David S. Draper, & M. Darby Dyar	Completed
Venus STDT Final Report	Mark Bullock & Dave Senske	Completed
Constraining Crustal Evolution from orbit	Jim Garvin	In progress
Astrobiology (to be coordinated by NASA Astrobiology Institute)	David Grinspoon for Venus Habitability	Completed
Inner-Solar System Habitability	David Grinspoon for Venus	In progress

To access papers, go to: www.lpi.usra.edu/vexag (note: endorsements in work)

VEXAG Community White Paper Venus Exploration Goals, Objectives, Investigations, and Priorities

This document is based on community input from 3 VEXAG public meetings. Focus groups on the atmosphere, the solid planet, and technologies developed a set of Goals and prioritized Objectives and Investigations.

This document has recently been revised to include:

- updates from the Venus Flagship report by the VSTDT
- the Venus Express Mission
- the recent Venus Geochemistry Workshop, and
- revised and prioritized objectives and investigations from the February VEXAG meeting.
- The technology section has been split off to create a separate white paper.

A system is being set up for on-line endorsement of papers.

Why Venus? Why now?

Venus as a case study of a terrestrial planet

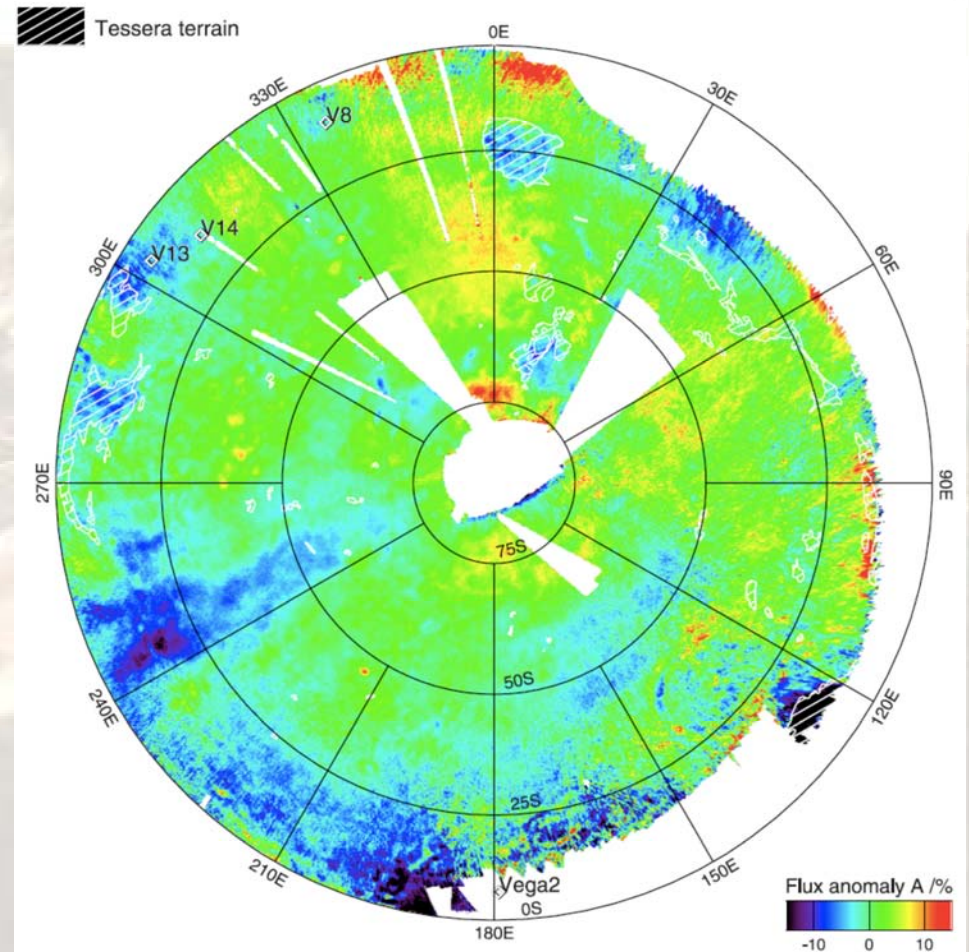
- *Venus challenges our ideas of how a terrestrial planet should behave and the factors that shape planetary evolution.*
 - The study of the early evolution of Venus can help elucidate the role of deterministic vs. stochastic effects of early impacts and volatile inventory.
 - The lack of plate tectonics on Venus has helped shape our understanding of the requirements for plate tectonics and the role of rheology and volatiles.
 - Venus may well have had an ocean, and thus have been habitable, up until ~1 b.a., much longer than water was abundant on Mars.
 - Venus is also an excellent place to study the interaction between the interior, outgassing, and climate (see next slide).
 - Venus' atmospheric dynamics should be simple: Venus has no significant seasons, no land-ocean contrast, uniform cloud cover and slow rotation, yet we do not have a good understanding of its workings.
 - Venus' ultraviolet absorber remains unknown, as well as why it is so highly variable in space and time and how the circulation is maintained.
- *As we explore other other solar systems, we can begin to assess whether Venus, Earth, or both planets are anomalous.*

Why Venus? Why now?

Venus Express Results

- Venus Express has renewed excitement over Venus science, revealing:

- Extremely high D/H ratio above clouds that might have clues about loss of water
- New observations of escaping H and O with implications for history of water
- Discovery of magnetic signals believed to be signature of frequent lightening bursts
- Vortex circulation hemispheric symmetry observed and evidence of dynamical instability due to horizontal wind shear (presence of a jet).
- Surface emissivity variations are consistent with more silica-rich tessera highlands (continents=oceans?!) and either variations in surface composition or relatively unweathered volcanic flows.



Mueller et al., 2008

dpa

Why Venus? Why now?

Venus, Earth and Climate Change

- Venus is an extreme case of global warming.
 - Provides an active example of runaway greenhouse warming and the role of cloud-climate feedback
- Venus provides our closest (and only) planetary analog for many important terrestrial climate processes.
 - Ozone loss on the Earth was discovered due to the study of Venus upper atmospheric chemistry
- Simulating the extreme climate of Venus can:
 - help to validate terrestrial general circulation models and increase understanding of nonlinear climate feedbacks
 - expose limitations of current climate models.
- Many scientific problems of common interest to both Venus and Earth climate studies:
 - Aerosol microphysics and radiative properties, cloud morphologies and climate forcings, mesoscale and vortex dynamics, atmospheric responses to short and long term solar forcing
 - Volcano-climate interactions
 - Atmospheric angular momentum and exchange with solid planet
 - Venus dynamical phenomena compared Earth stratospheric oscillations

Why Venus? Why now?

Venus measurements are becoming obsolete..

- Landers first explored the geochemistry of the surface ~25 years ago.
 - Huge advances in instrumentation make it imperative to update the quality of geochemical and geological measurements to a level comparable to in-situ exploration of Mars and the Moon.
 - These measurements suggest tantalizing clues about surface composition, such a high K basalts, but error bars are such that these results are suspect.
 - More recent data suggest more informed landing site choices may be reveal compositional variations.
 - Unlike the other terrestrial planets, Venus' cloud cover prohibits a thorough investigation of the mineralogy and elemental composition from orbit.
 - Further, Venus lacks surface samples in the form of meteorites.
- Altimetry and SAR measurements are more than an order of magnitude poorer resolution than comparable measurements for Mars, the Moon, and Mercury
- Lack of US missions means that few young scientists study Venus...

Science Theme:

Venus and Implications for the Formation of Habitable Worlds.

This theme is supported by three goals:

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

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

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

Goal 1: Origin and Evolution

- **How did Venus originate and evolve, and what are the implications for the characteristic lifetimes and conditions of habitable environments on Venus and similar extrasolar systems?**
- Objective 1: Understand atmospheric evolution
 - Has the atmosphere been affected by solar wind erosion? Major impacts? Has there been hydrodynamic escape of an ocean?
 - How has outgassing shaped the atmosphere? How does the level compare to that of Earth?
- Objective 2: Seek evidence for changes in interior dynamics
 - Did Venus ever have plate tectonics?
 - What lead to the development of a stagnant lid?
- Objective 3: Determine if Venus was ever habitable
 - Are there minerals or rocks that formed in water or have been altered by water?
 - Are there trapped gasses that reflect past atmospheric conditions?

Goal 1: Origin and Evolution

Goal	Objective	Investigation	Platform
Origin and Evolution	Understand atmospheric evolution	Characterize elemental composition and isotopic ratios of noble gases in the Venus atmosphere, especially Xe, Kr, ^{40}Ar , ^{36}Ar , Ne, ^4He , ^3He , to constrain origin and sources and sinks driving evolution of the atmosphere.	Probe, Balloon
		Determine isotopic ratios of H/D, $^{15}\text{N}/^{14}\text{N}$, $^{17}\text{O}/^{16}\text{O}$, $^{18}\text{O}/^{16}\text{O}$, $^{34}\text{S}/^{32}\text{S}$ and $^{13}\text{C}/^{12}\text{C}$ in the atmosphere to constrain paleochemical disequilibria, atmospheric loss rates, the history of water, and paleobiosignatures.	Probe, Balloon
	Seek evidence for past changes in interior dynamics	Characterize the structure, dynamics, and history of the interior of Venus, including possible evolution from plate tectonics to stagnant-lid tectonics.	Orbiter, lander
		Characterize the nature of surface deformation over the planet's history, particularly evidence for significant horizontal surface movement.	Orbiter
		Characterize radiogenic ^4He , ^{40}Ar and Xe isotopic mixing ratios generated through radioactive decay to determine the mean rate of interior outgassing over Venus's history.	Probe, Balloon
	Determine if Venus was ever habitable	At the surface, identify major and minor elemental compositions (including H), petrology, and minerals in which those elements are sited (for example, hydrous minerals to place constraints on past habitable environments).	Lander
		Characterize gases trapped in rocks for evidence of past atmospheric conditions.	Lander

Goal 2: Venus as a Terrestrial Planet

- Objective 1: Understand what the chemistry and mineralogy of the crust tell us about processes that shaped the surface of Venus over time
 - What is the size of the core?
 - Is there a secondary, silica-rich crust (e.g. 'continents')?
 - What is variation in crustal composition? Has the composition changed over time?
 - Are there active plumes or other distinct tectonic settings?
 - What is the abundance of radiogenic elements?
 - What is the high reflectivity material at high elevations?

Goal 2: Venus as a Terrestrial Planet

Objective 1

Goal	Objective	Investigation	Platform
Venus as a Terrestrial Planet	Understand what the chemistry and mineralogy of the crust tell us about processes that shaped the surface of Venus over time	Characterize geologic units in terms of major, minor, and selected trace elements (including those that are important for understanding bulk volatile composition, conditions of core formation, heat production, and surface emissivity variations), minerals in which those elements are sited, & isotopes.	Lander
		Characterize the chemical compositions of materials near Venus's surface as a function of depth (beyond weathering rind) to search for evidence of paleochemical disequilibria and characterize features of surface rocks that may indicate past climate or biogenic processes.	Lander
		Assess the petrography (shapes, sizes, & mineral grain relationships) & petrology (formation characteristics) of surface rocks to aid in interpretation of chemical and mineralogical characterization.	Lander
		Determine the physical properties and mineralogy of rocks located in a variety of geologic settings, including meteoritic and crater ejecta, volcanic flows, aeolian deposits, and trace metals in the high radar reflectivity highlands.	Lander
		Characterize surface exposure ages through measurements of weathering rinds.	Lander

Goal 2: Venus as a Terrestrial Planet

- Objective 2: Assess the current structure and dynamics of the interior
 - What is the radius of the core?
 - What caused Venus to resurface?
 - Is resurfacing on-going today? What are the rates and scales?
 - What is the structure of the crust? How is the crust affected by stagnant lid convection?
 - Was there every a dynamo? If crustal remenant magnetization exists, what does it tell us about geologic processes?

Goal 2: Venus as a Terrestrial Planet

Objective 2

Goal	Objective	Investigation	Platform
Venus as a Terrestrial Planet	Assess the current structure and dynamics of the interior	Characterize the current structure and evolutionary history of the core.	Lander, Orbiter
		Place constraints on the mechanisms and rates of recent resurfacing and volatile release from the interior.	Orbiter
		Determine the structure of the crust, as it varies both spatially and with depth, through measurements of topography and gravity to high resolution.	Orbiter
		Measure heat flow and surface temperature to constrain the thermal structure of the interior.	Lander
		Measure the magnetic field below the ionosphere and characterize magnetic signature of rocks in multiple locations.	Balloon, Orbiter
		Characterize subsurface layering and geologic contacts to depths up to several km.	Orbiter
		Determine the moment of inertia and characterize spin-axis variations over time.	Orbiter, Lander

Goal 2: Venus as a Terrestrial Planet

- Objective 3: Characterize the current rates and styles of volcanism and tectonism, and how have they varied over time
 - How geologically active is Venus today?
 - How and why did Venus resurface?
 - What are the current scales and rates of resurfacing?
 - What is the current rate of outgassing?
- Objective 4: Characterize current processes in the atmosphere
 - What causes and maintains superrotation?
 - What is the radiative balance and how is momentum exchanged?
 - What is the UV absorber? What are its sources and sinks?

Goal 2: Venus as a Terrestrial Planet

Objective 3

Goal	Objective	Investigation	Platform
Venus as a Terrestrial Planet	Characterize the current rates and styles of volcanism and tectonism, and how have they varied over time	Characterize active-volcanic processes such as ground deformation, flow emplacement, or thermal signatures to constrain sources and sinks of gases affecting atmospheric evolution.	Orbiter
		Characterize active-tectonic processes through seismic, ground motion, or detailed image analysis.	Lander, Orbiter
		Characterize the materials emitted from volcanoes, including lava and gases, in terms of chemical compositions, chemical species, and mass flux over time.	Orbiter
		Characterize stratigraphy of surface units through detailed topography and images.	Orbiter, Balloon
		Assess geomorphological, geochemical, and geophysical evidence of evolution in volcanic styles.	Orbiter, Lander, Balloon

Goal 2: Venus as a Terrestrial Planet

Objective 4

Goal	Objective	Investigation	Platform
Venus as a Terrestrial Planet	Characterize current processes in the atmosphere	Characterize the sulfur cycle through measurements of abundances within the Venus clouds of relevant gaseous and liquid/solid aerosol components such as SO ₂ , H ₂ O, OCS, CO, and sulfuric acid aerosols (H ₂ SO ₄).	Probe
		Determine the mechanisms behind atmospheric loss to space, the current rate, and its variability with solar activity.	Orbiter
		Characterize local vertical winds and turbulence associated with convection and cloud-formation processes in the middle cloud region, at multiple locations.	Balloons
		Characterize superrotation through measurements of global-horizontal winds over several Venus days at multiple-vertical levels (day and night) from surface to thermosphere.	Balloons
		Investigate the chemical mechanisms for stability of the atmosphere against photochemical destruction of CO ₂ .	Probe, Balloon
		Characterize local and planetary-scale waves, especially gravity waves generated by underlying topography.	Balloons
		Measure the frequencies and strengths of lightning and determine role of lightning in generating chemically-active species (e.g., NO _x).	Orbiter
		Search for and characterize biogenic elements, especially in the clouds.	Balloon, Probe

Goal 3: Climate Change and the Future of Earth

- Objective 1: Characterize the Venus Greenhouse
 - Where and how in the atmosphere is solar energy absorbed?
 - How do the global dynamics of the atmosphere affect the radiative balance?
 - What is the role of volcanic outgassing and surface-atmosphere interactions in maintaining the current climate?
- Objective 2: Determine if there was ever liquid water on the surface of Venus
 - How does the current chemistry and mineralogy of the surface reflect the ancient volatile history of the surface?
 - Could there be metastable hydrated minerals on the surface?
 - Are there isotopic clues in surface materials that record an ancient oceans?
- Objective 3: Characterize how the interior, surface, and atmosphere interact
 - What are the current outgassing fluxes of H₂O, SO₂ and other gases?
 - To what depth are bedrock outcroppings chemically weathered?
 - Are there long-term climate feedbacks involving volcanic activity and interior depth of melting?
 - Is there evidence for climate-mediated geological activity?

Goal 3: Climate Change and the Future of Earth

Goal	Objectives	Investigations	Platform
Climate Change and the Future of Earth	Characterize the Venus Greenhouse	Determine radiative balance as a function of altitude, latitude, and longitude.	Balloon, probe
		Measure deposition of solar energy in the atmosphere globally.	Balloon, probe
		Determine the size, distribution, shapes, composition, and UV, visible, and IR spectra, of aerosols through vertical profiles at several locations.	Probe
		Determine vertical-atmospheric temperature profiles and characterize variability.	Probe
	Determine if there was ever liquid water on the surface of Venus	Determine isotopic ratios of H/D, $^{15}\text{N}/^{14}\text{N}$, $^{17}\text{O}/^{16}\text{O}$, $^{18}\text{O}/^{16}\text{O}$, $^{34}\text{S}/^{32}\text{S}$ $^{13}\text{C}/^{12}\text{C}$ in solid samples to place constraints on past habitable environments (including oceans).	Balloon, probe
		Identify and characterize any areas that reflect formation in a geological or climatological environment significantly different from present day.	Orbiter
	Characterize how the interior, surface, and atmosphere interact	Determine abundances and height profiles of reactive atmospheric species (OCS, H ₂ S, SO ₂ , SO ₃ , H ₂ SO ₄ , S _n , HCl, HF, SO ₃ , ClO ₂ and Cl ₂), greenhouse gases, H ₂ O, and other condensibles, in order to characterize sources of chemical disequilibrium in the atmosphere.	Balloon, probe
		Determine rates of gas exchange between the interior, surface and atmosphere.	Balloon, probe, lander

Venus in the Discovery Program

- Numerous important science objectives can be addressed at Venus within Discovery!
- Examples include:
 - Atmospheric dynamics: Meridional and zonal winds, waves, thermal tides, etc
 - Atmospheric chemistry: Noble gasses and their isotopes, trace gas species such as those in the sulfur cycle
 - Volcanism and resurfacing
 - Interior structure (non-seismic)
 - Radiative balance and greenhouse effect
- Areas clearly outside of Discovery include those that require landers, long surface life, or multiple platforms (other than multiple balloons)

Venus New Frontiers Mission Concepts

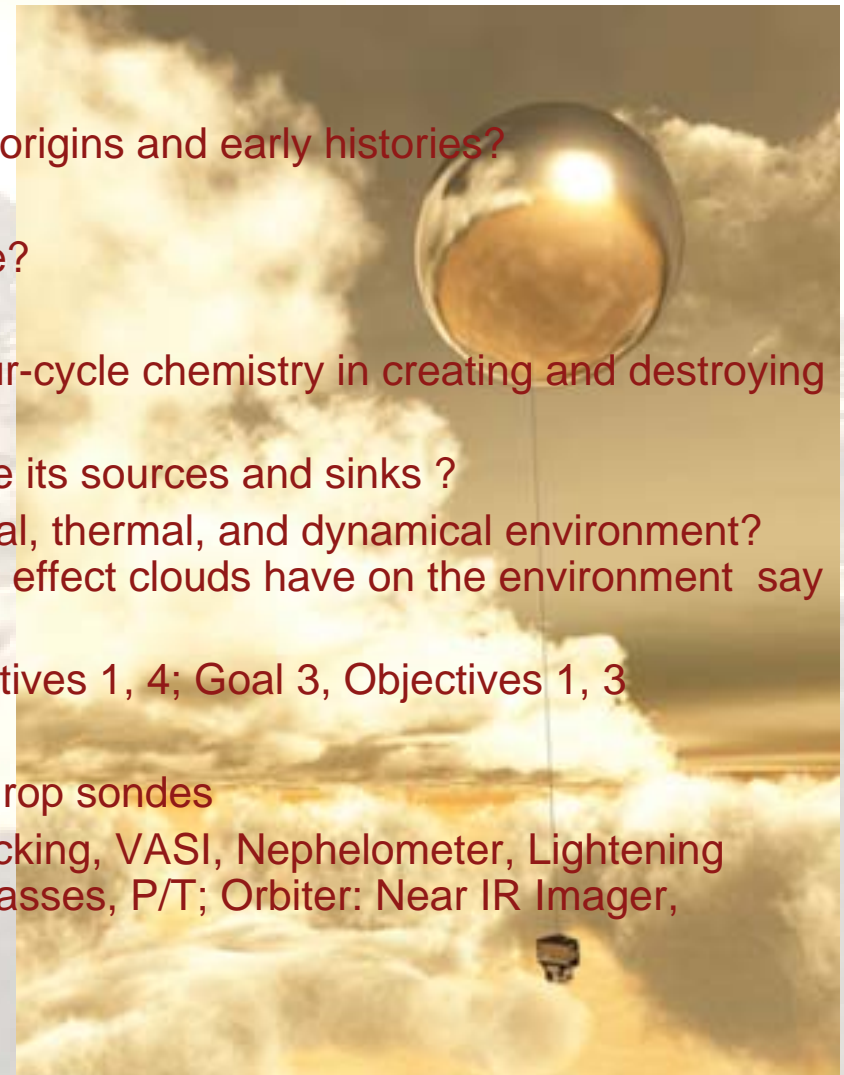
- Venus In-Situ Explorer (VISE)
- Venus Atmospheric Explorer
- Venus Global Surveyor (for Geophysics, Volcanology, and Tectonics)
- Venus Atmospheric Sample Return
- Next Generation Geochemical Lander (VISE Mark II)
- Geophysical Lander
-combinations of the Flagship mission elements...

Venus In-Situ Explorer

- **Overarching Science:** What can Venus tell us about the accretion of the terrestrial planets; Did Venus have an ocean; What is the surface weathering on Venus; What's the style of emplacement and composition of volcanics; How did the atmospheric chemistry evolve? Model the past Venus history and extend it to the future of Venus, Mars and Earth. Define the observable characteristics of extrasolar planets like Venus.
- **Science Questions:**
 1. Measure noble gases and their isotopes to constrain Venus history
 2. Measure trace gas profiles and sulfur compounds for chemical cycles and surface-atmosphere interactions
 3. Meteorological measurements to the surface
 4. Measure surface and sub-surface composition
 5. Constrain the coupling of radiation, dynamics and chemistry
 6. Compare the terrestrial planets in detail to predict and characterize extra-terrestrial planets
- **VEXAG:** Goal 1, Objective 3; Goal 2, Objective 1, 4; Goal 3, Objective 3
- **Implementation:** Lander, with sampling during descent
- **Instruments:** Cameras, spectrometers, NMS/GC, meteorology package, determine mineralogy, elemental composition, and surface texture.

Venus Atmospheric Explorer

- **Overarching Science:** How does the Venus atmosphere work?
- **Science Questions:**
 - How similar were Venus and Earth in their origins and early histories?
 - What causes and maintains superrotation?
 - How has the atmosphere evolved with time?
 - Is there outgassing from the interior?
 - What is the interplay of dynamics and sulfur-cycle chemistry in creating and destroying clouds?
 - Clouds: what is the UV absorber? What are its sources and sinks ?
 - How sensitive is cloud cover to the chemical, thermal, and dynamical environment? What does this sensitivity and the radiative effect clouds have on the environment say about climate change on Venus?
- **VEXAG:** Goal 1, Objectives 1, 2; Goal 2, Objectives 1, 4; Goal 3, Objectives 1, 3
- **Implementation:**
 - Long-lived multi-level balloons plus orbiter & drop sondes
- **Instruments:** balloon: GCMS, TLS, Radio Tracking, VASI, Nephelometer, Lightning detector; Drop Sonde: Near IR camera, trace gasses, P/T; Orbiter: Near IR Imager, topographic radar



Venus Global Surveyor (VGS) *for geophysics, volcanology, tectonics*

- **Overarching Science:** Determine the evolution of Venus crust and shallow interior as well as the role of crustal resurfacing, including whether active volcanism persists today
- **Science Questions:**
 - How did the crust of a neighboring Earth-sized planet evolve in space and time?
 - Did Venus experience global-scale crustal resurfacing that modified its observed crater population, and how does crustal resurfacing apply to the history of Earth before the Phanerozoic (Proterozoic overplating?)
 - How does planetary size impact thermal and magmatic evolution?
 - Are there signatures of past hydrologic cycles (if any) preserved in the crustal record?
- **VEXAG:** *Goal 1, Objective 2. Goal 2, Objective 2,3. Goal 3, Objective 2*
- **Implementation:** Magellan-class spacecraft in circular orbit
- **Instruments:** Multi-beam High Frequency Radar altimeter; High-bandwidth Polarimetric Imaging Radar (SAR); Near-IR Imaging Spectrometer [Heritage from Cassini, LRO, OSTM, CryoSat-II instruments, plus Precision Orbit Determination from MGS, MRO, LRO]

Venus Atmospheric Sample Return

- **Overarching Science:** Determine the origin and evolution of Venus' atmosphere
- **Science Questions:**
 - How did the primary atmospheres of inner solar system planets form?
 - Have all the terrestrial planets experienced early catastrophic loss followed by the formation of secondary atmospheres?
 - How does distance from the sun or existence of an ocean affect the early evolution of planetary atmospheres?
- **VEXAG:** Goal 1, Objective 1,3. Goal 2, Objective 4. Goal 3, Objective 2
- **Implementation:** Capsule captures 1 liter of Venus atmosphere from 110 km during flyby and returns it to Earth. Sample temperature is stabilized in non-reactive vessel for return. Very high precision mass spectroscopy would be used in Earth-based laboratories to acquire all noble gas isotope abundances. These record the very early history of violent atmospheric loss of Venus, due to a large impact or hydrodynamic escape of an ocean.
- **Instruments:** Radio science and camera, sample return capsule

Next Generation Geochemical Lander

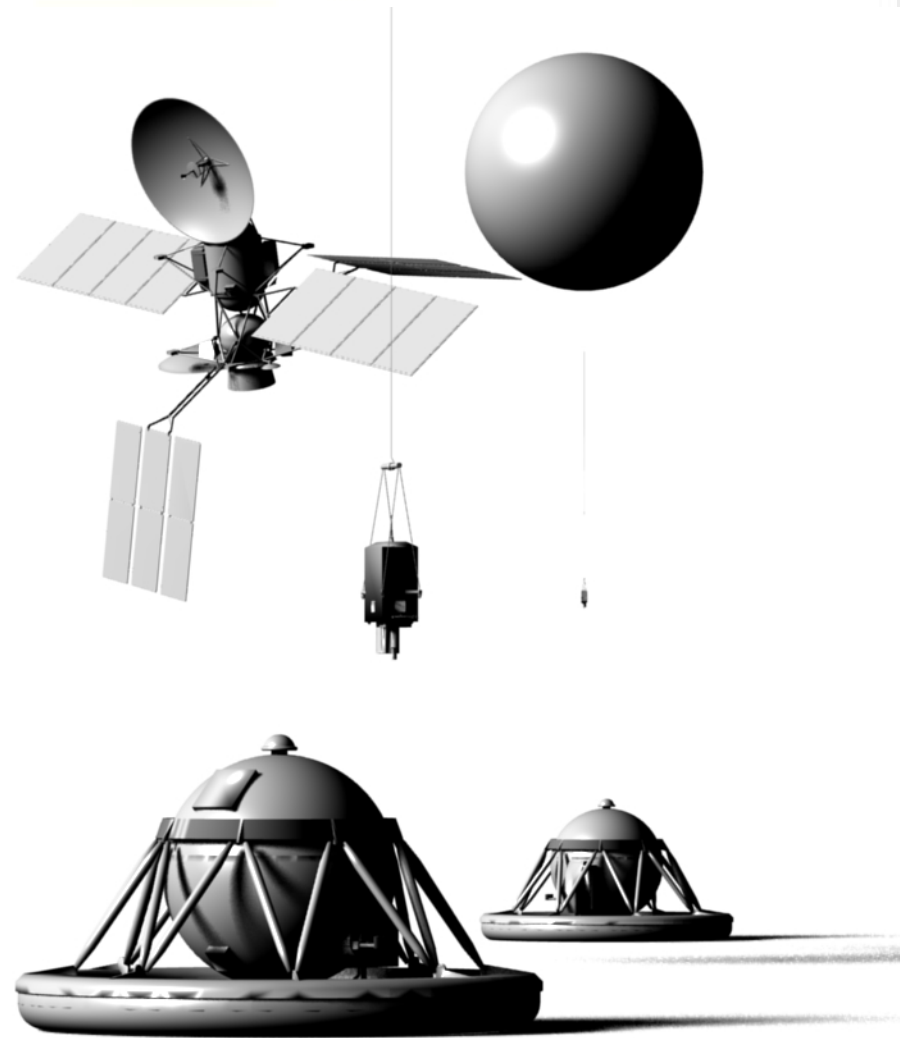
- **Science:** Mineralogy, geochemistry, and trapped gasses from the surface and surface and subsurface
- **Science Questions:**
 - How have the atmosphere and surface chemically interacted?
 - Is there evidence for changes in climate in the geochemical record?
 - How was the crust formed?
 - Is there evidence for a lost ocean?
 - What is the rate of weathering?
- **VEXAG:** Goal 1: Objectives 1,2,3. Goal 2: Objectives 1,4. Goal 3: Objectives 2,3
- **Implementation:** 24 hour passively-cooled lander with robotic sampling arm and 10 cm-depth drill. Humans in the loop for selecting sampling sites. Target: Vesicular basalt to examine trapped gasses.
- **Instruments:** XRD, XRF, Mass spec, descent and panoramic cameras, microscopic camera.

Geophysical Lander

- **Overarching Science:** Interior Structure and Thermal Evolution
- **Science Questions:**
 - What is the structure of the crust?
 - What is the rate of interior heat flow?
 - What is the distribution of radiogenic elements?
 - What is the size and state of the core?
- **VEXAG:** Goal 1, Objective 2, Goal 2, Objective 2,3
- **Implementation:** Lander
- **Instruments:** Corner Cube Reflector, Magnetometer, EM Sounding, Heat flow, Panoramic Camera, Gamma Ray Spectrometer

Future Flagships

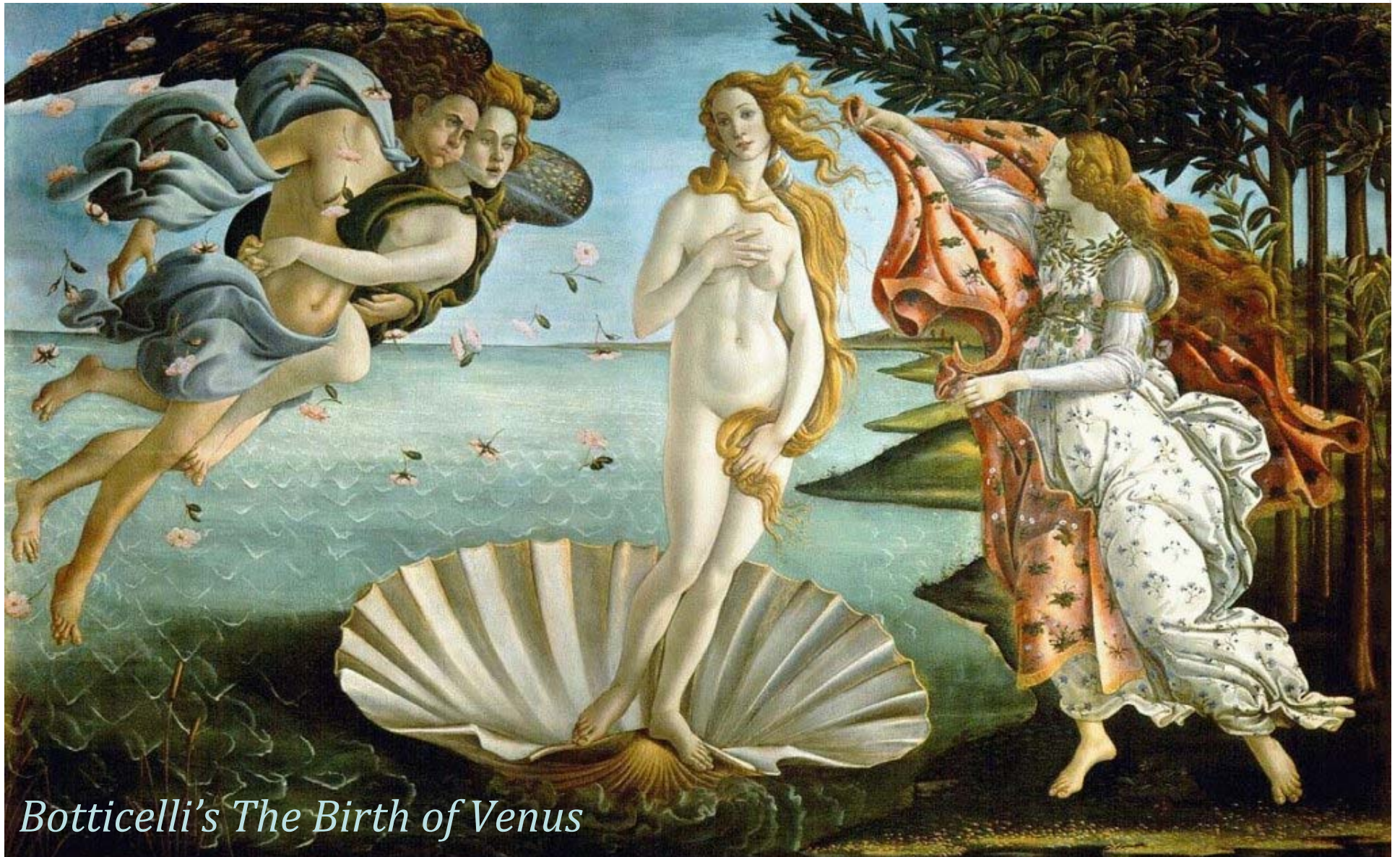
- See Mark Bullock's presentation on the recent Venus' Flagship Study.
- Additionally, network missions are essential to understanding interior structure and atmospheric dynamics. This science continues to be high priority. For Venus, significant technology development is required to enable these types of missions.



Summary of Upcoming VEXAG Activities

- Inputs to Decadal Survey: white papers & mission concepts
- Following up on recommendations from Flagship STDT
- Support Comparative Climatology Initiative: Chapman Conf. in 2011
- Develop international links and cooperation
 - Venus Climate Orbiter to be launched by JAXA in May, 2010
 - Venera-D is under development in Russia
 - European Venus Explorer (EVE) will be repropoed to the Cosmic Vision Program in 2010
- Brief community meetings planned for DPS and AGU
- **Next (7th) VEXAG Meeting:**
 - October 28–29, 2009
 - Irvine, California
 - In conjunction with the Next NRC DS Panel meeting on October 27–28, 2009

Venus is a mythical planet, ready to give birth to fully grown mission concepts at all levels!



Botticelli's The Birth of Venus