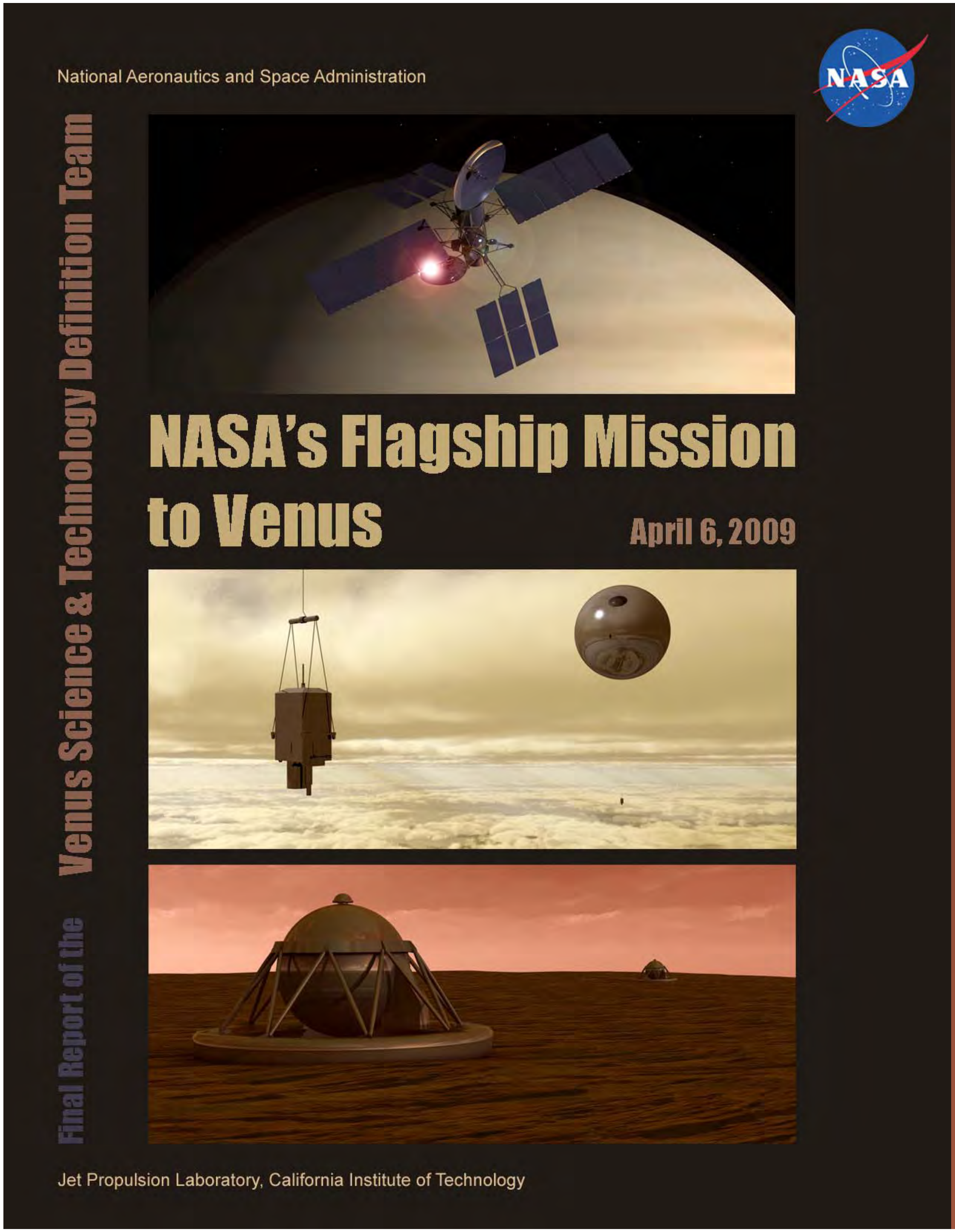


A Flagship Mission to Venus

Report of the Venus Science and Technology Definition Team

NRC Decadal Survey
IPP, August 27, 2009

Presentation Outline

The Venus STDT	Bullock	Chapter 1
Open Science Questions	Bullock	Chapter 2
Venus Flagship Science Objectives	Bullock	Chapter 2-3
The Design Reference Mission	Balint	Chapter 4
Technology Challenges	Balint	Chapter 4-5
Design Reference Mission Science Performance	Bullock	Chapter 4
Summary	Bullock	Chapter 6
Recommendations for Future Work	Bullock	Chapter 5

Venus STDT Objectives

- Phase 1: Develop and Prioritize Science Objectives and Investigations for a Venus flagship mission drawing upon
  - VEXAG White Paper (2007)
  - NRC Decadal Survey (2003) and NOSSE update (2008)
  - NASA's SSE Roadmap (2006)
- Phase 1: Identify the optimal architecture to achieve science objectives
- Phase 2: Execute the Design Reference Mission design from a science-driven architecture trade
  - Design and assess scientific performance of payload
  - Assess Performance, Cost, Risk, and Technology Readiness
- Phase 2: Identify Technology Development
  - To fully execute the Design Reference Mission
  - For alternate payloads and architectures

Venus STDT Membership

Chairs: Mark Bullock (SwRI) and Dave Senske (JPL)

- **Atmosphere**
  - **David Grinspoon** (DMNS)
  - Anthony Colaprete (NASA Ames)
  - Sanjay Limaye (U. Wisconsin)
  - George Hashimoto (Japan)
  - Dimitri Titov (ESA)
  - Eric Chassefiere (France)
  - Hakan Svedhem (ESA)
- **Geochemistry**
  - **Allan Treiman** (LPI)
  - Steve Mackwell (LPI)
  - Natasha Johnson (NASA))
- **Geology and Geophysics**
  - **Dave Senske** (JPL)
  - Jim Head (Brown University)
  - Bruce Campbell (Smithsonian)
  - Gerald Schubert (UCLA)
  - Walter Kiefer (LPI)
  - Lori Glaze (GSFC)
- **Technology**
  - **Elizabeth Kolawa** (JPL)
  - Viktor Kerzhanovich (JPL)
  - Gary Hunter (GRC)
  - Steve Gorevan (HoneyBee)
- **Ex Officio**
  - Ellen Stofan (VEXAG Chair)
  - Tibor Kremic (NASA)

JPL Venus Flagship Mission Architecture Study

Study Lead: Jeff Hall
Tibor Balint
Craig Peterson
Alexis Benz
Team X

NASA and JPL

Jim Cutts (JPL)
Adriana Ocampo (NASA HQ)

International Collaboration

- Multi-element architecture lends itself to international collaboration
- Timing for international collaboration:
  - NASA (Venus Flagship)
  - ESA (VEX Current-2011)
  - ESA (Cosmic Vision EVE > 2020)
  - JAXA (VCO 2010)
  - Russia (Venera D 2016)

Venus Flagship Mission Assumptions & Constraints

• Launch Opportunity:	2020 to 2025
• Technology Maturation:	TRL 6 by 2015
• Life Cycle Mission Cost Range:	$3 - 4B (FY ’08)
• LV Capability:	$\leq$ Delta IVH equiv.
• DSN Capability:	up to 34M, Ka band
• International Contribution:	No foreign cost contribution

- Assume no earlier missions prior to flight of the Venus Flagship Mission

Open Science Questions

Phase 1: Venus Flagship Science Investigations

Why is Venus so different from Earth?

- What does the Venus greenhouse tell us about climate change?
  - How do clouds and chemical cycles affect atmospheric energy balance?
  - What drives the atmospheric superrotation?
  - Is there evidence for climate change?

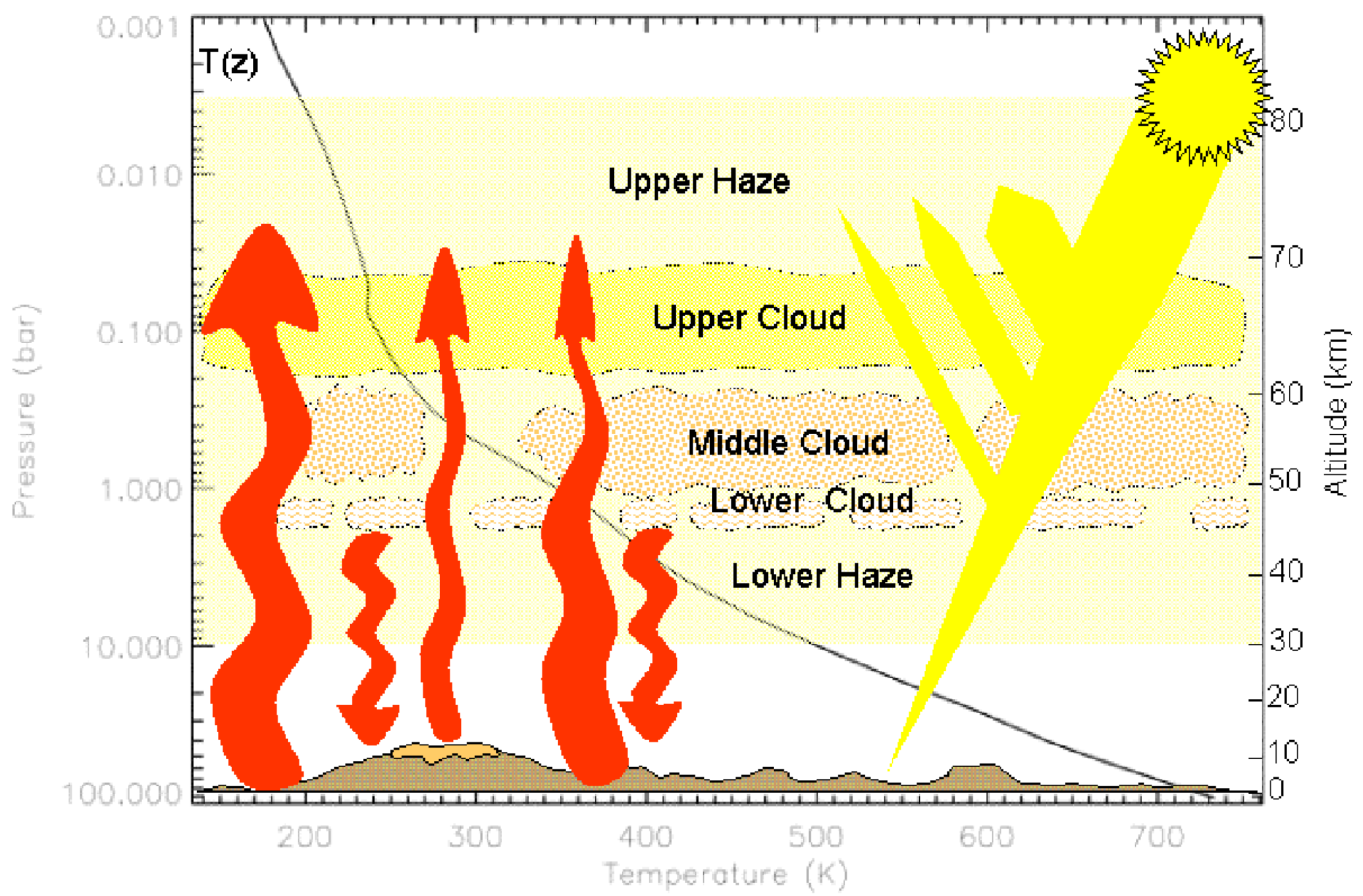
- How active is Venus?
  - Is Venus geologically active and what is it's geologic history?
  - How do surface/atmosphere interactions affect rock mineralogy and climate?
  - What is structure of the interior, and what are its dynamics?

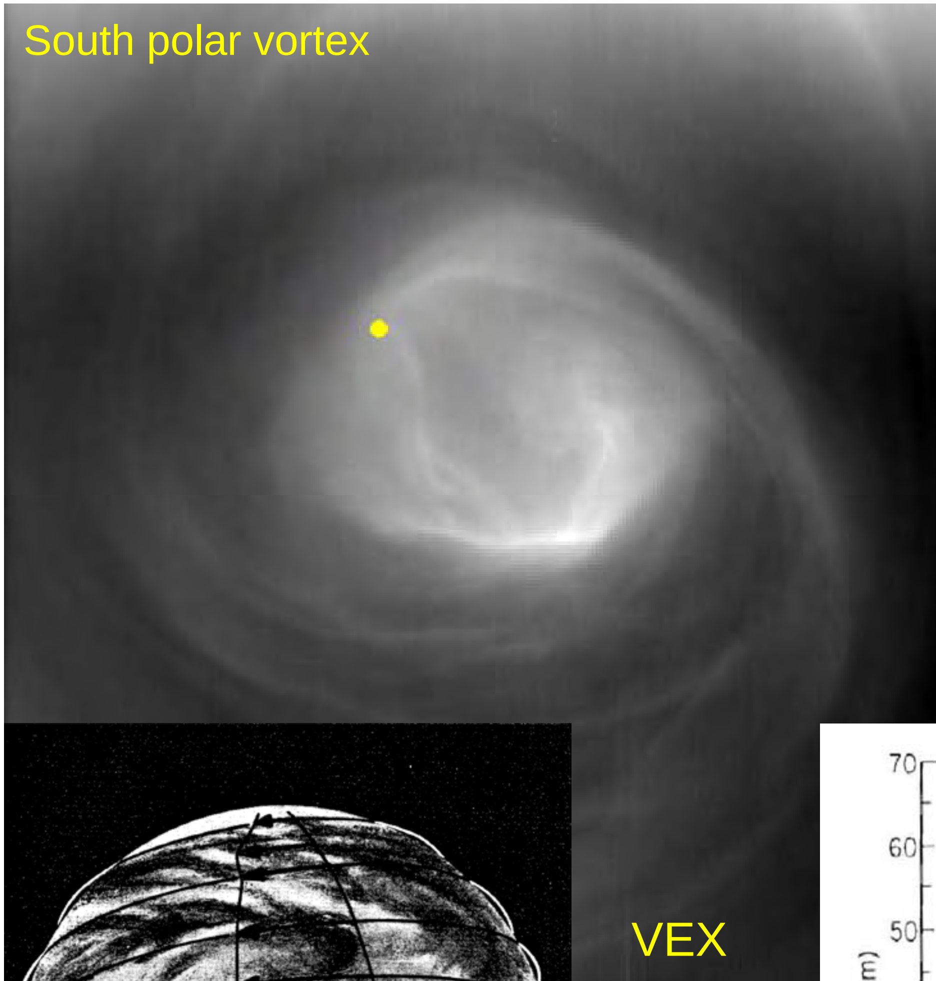
- When and where did the water go?
  - How did the early atmosphere evolve?
  - Did Venus have an ocean and if so, when was it lost?
  - Is there continent-like crust on Venus?

The Venus Greenhouse

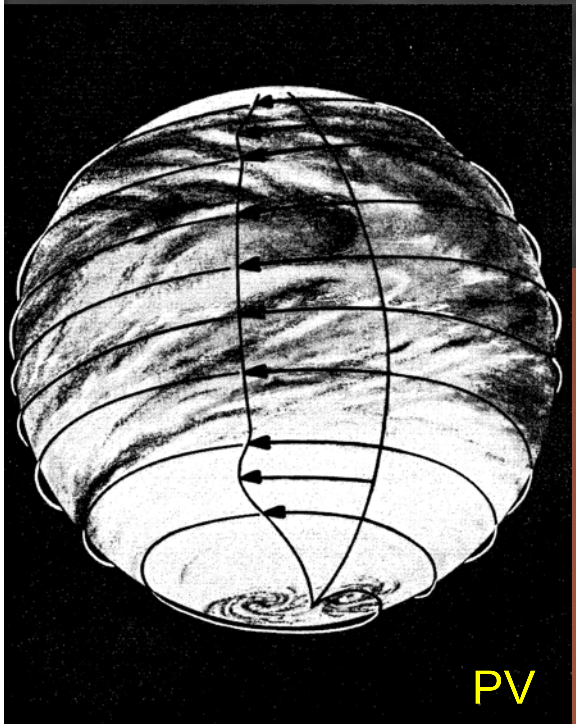
How does the greenhouse work, and has Venus experienced climate changes?

Mariner 10

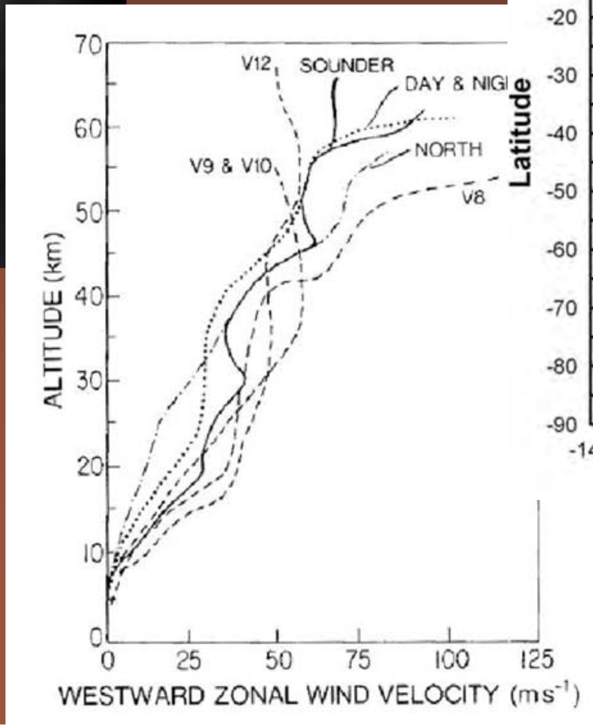


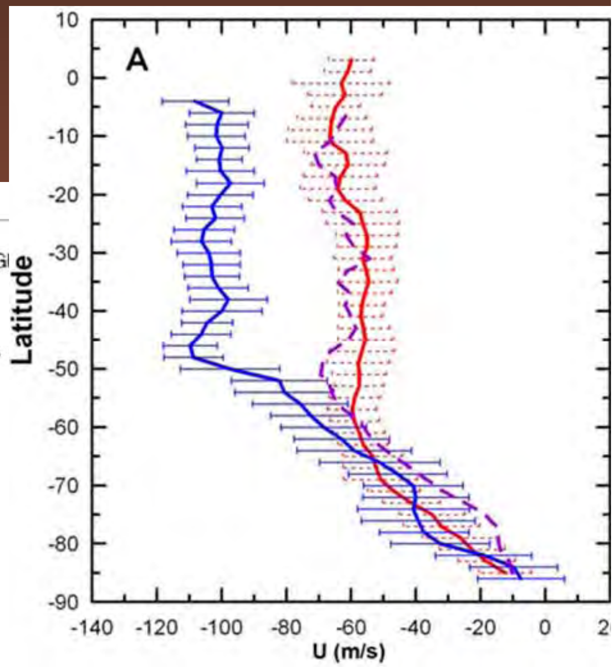


Why does the atmosphere superrotate?



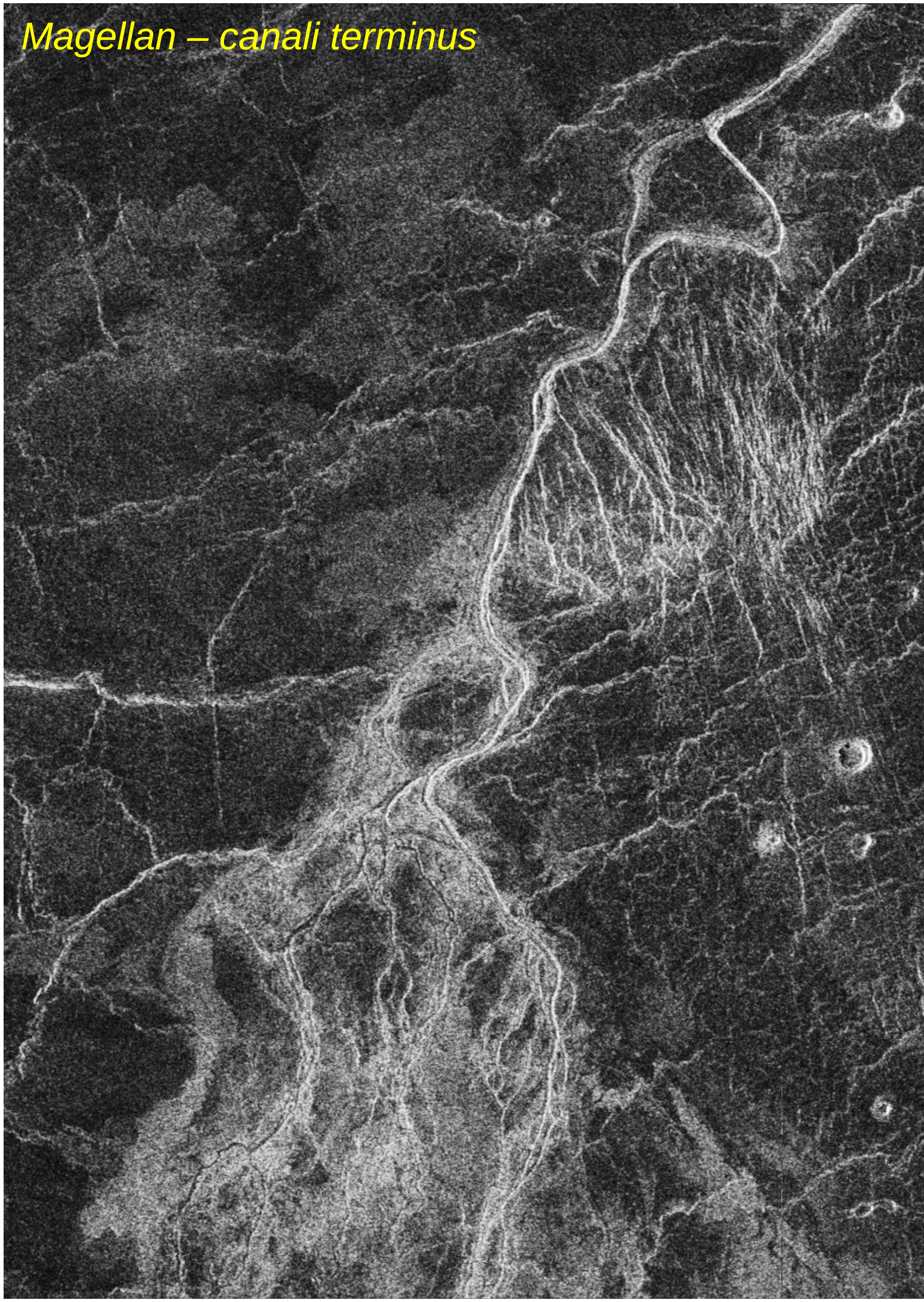
Probes: Winds decrease with altitude





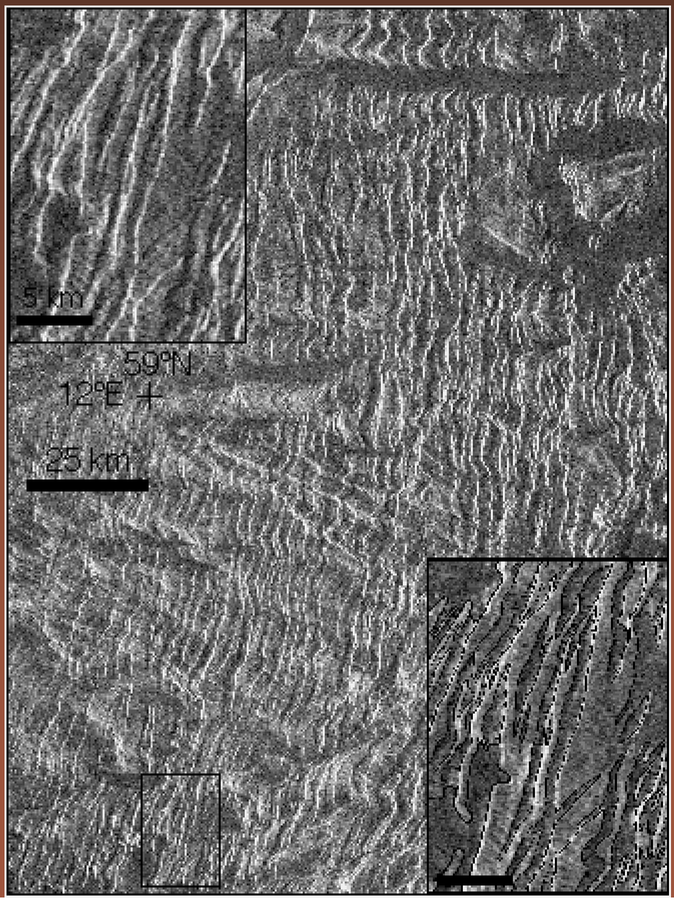
VEX East-west winds, decreasing at the poles

Magellan – canali terminus



Some surface features from Magellan hint at climate change

Magellan – Tessera terrain



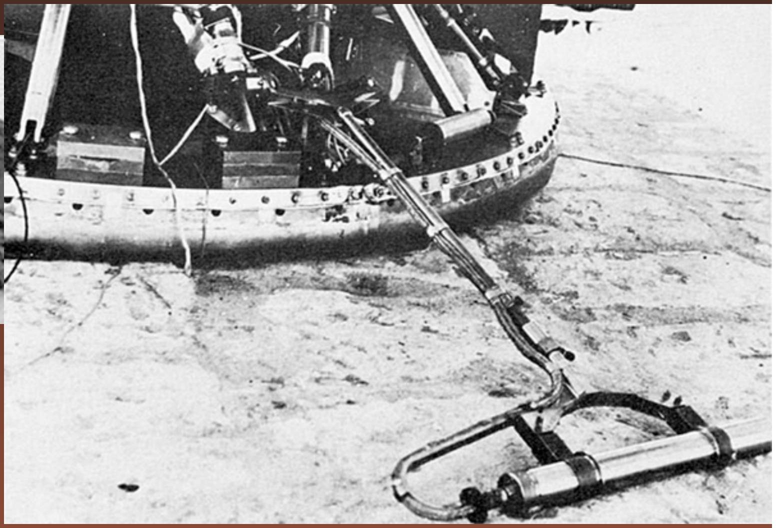
Is there evidence for climate change at the surface?

Weathered rock may hold the chemical clues

Processed Venera 13 panorama

How do the Surface and Atmosphere Interact?

Venera 9 γ-spectrometer in lab



Venera 9

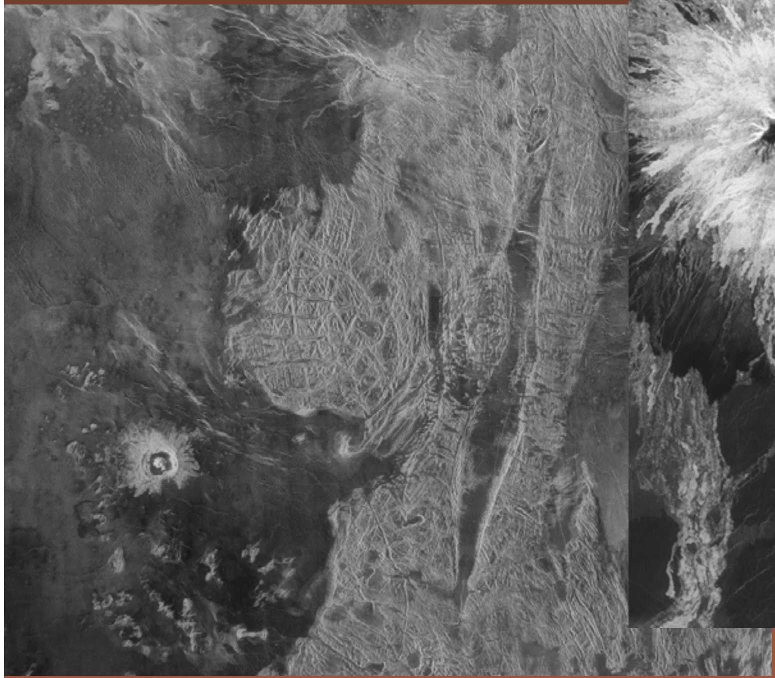
Rock slabs may show a natural chemical horizon from interactions with the atmosphere

Venera 14

Is Venus Geologically Active?

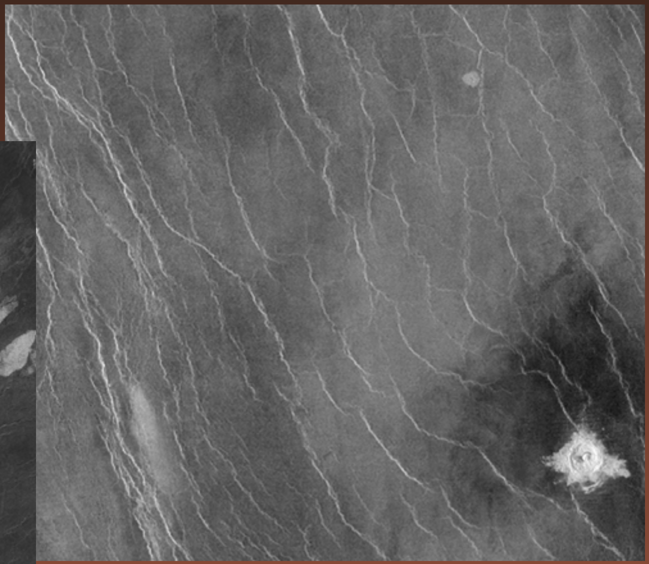
Magellan saw young volcanic features

Tessera

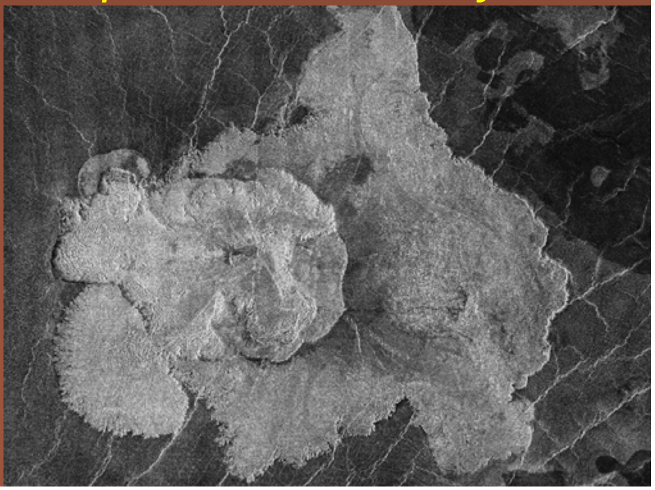


Volcanoes

Plains



Compositional Diversity



What is the structure of the interior?

Venus is covered with volcanic plains

It does not have plate tectonics

How does the heat get out?

How is the mantle thermally and mechanically coupled to the lithosphere?

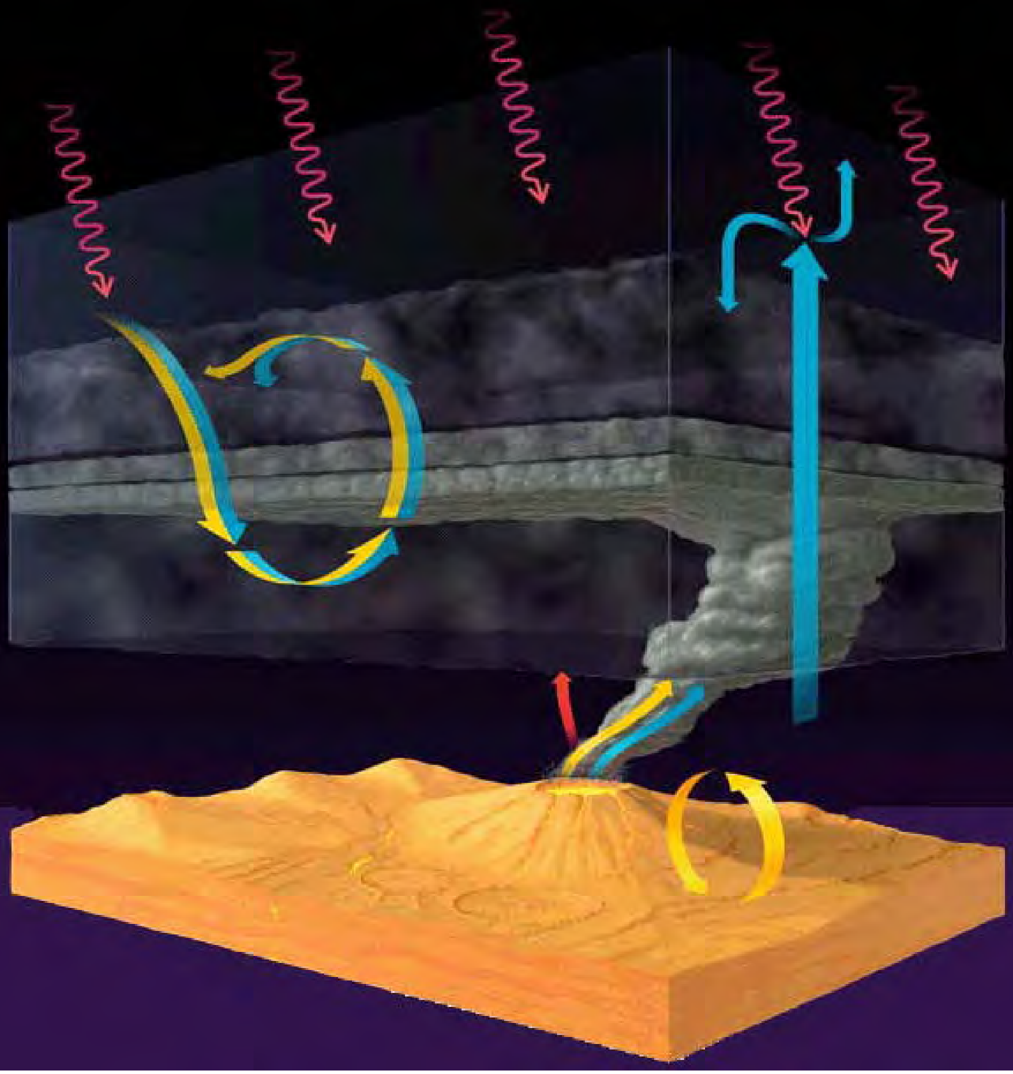
What destroyed the first 85% of Venus' surface history?

Geologic survey

Heat flux

Seismometry

How did early Venus evolve? Did it have oceans?



High D/H means Venus once had much more water.

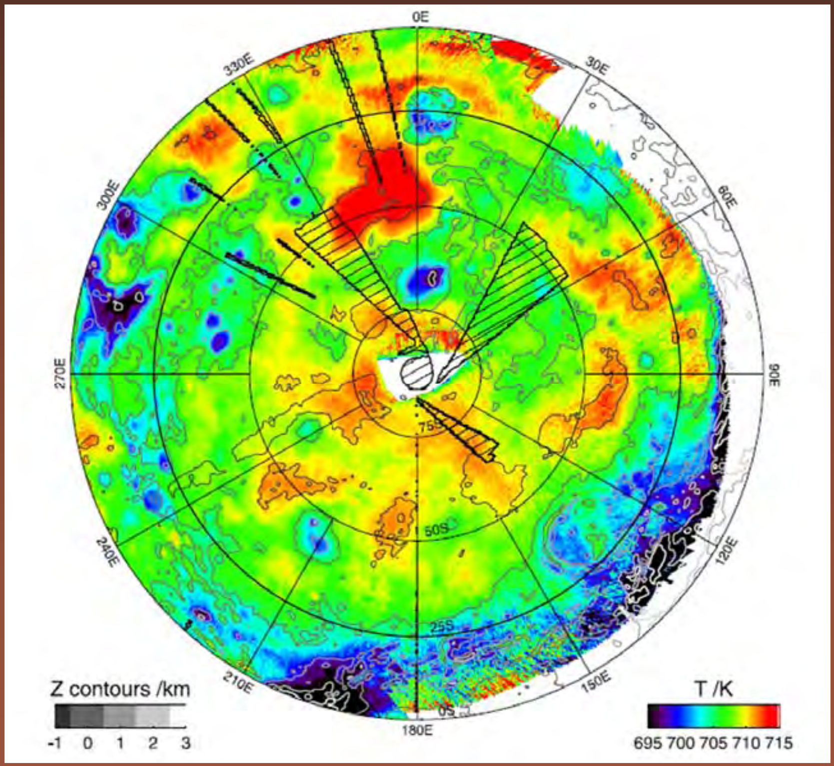
Venus' climate is an interconnected system of atmospheric, geologic, and surface chemistry processes, just like the Earth's.

Was Venus once habitable?

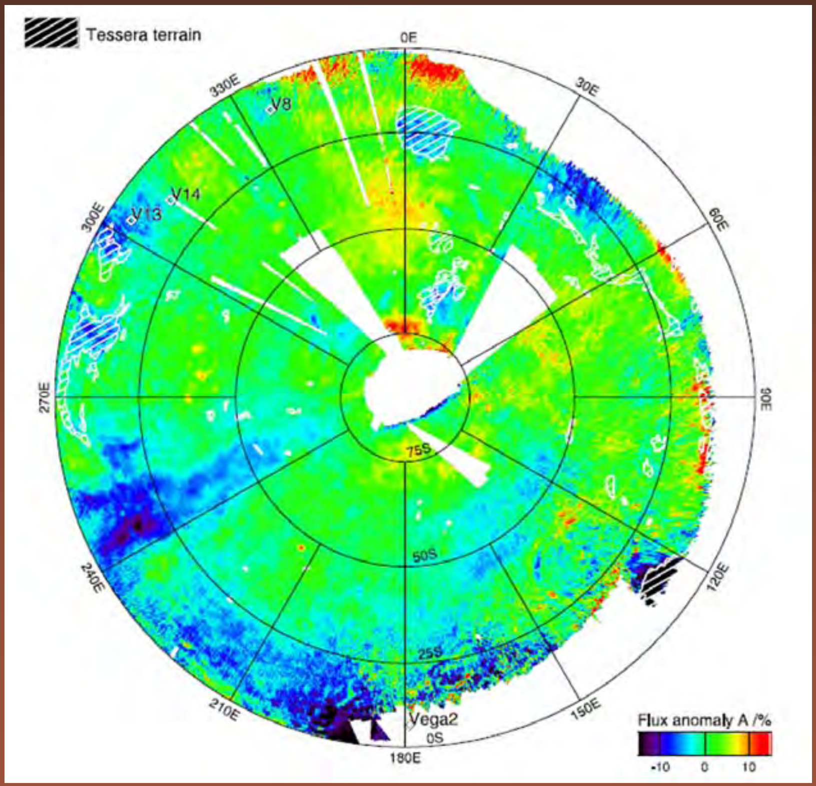
Is there continent-like crust on Venus?

Continental crust requires large amount of water in the mantle

Tessera have lower emissivity (felsic?) Young volcanics higher emissivity



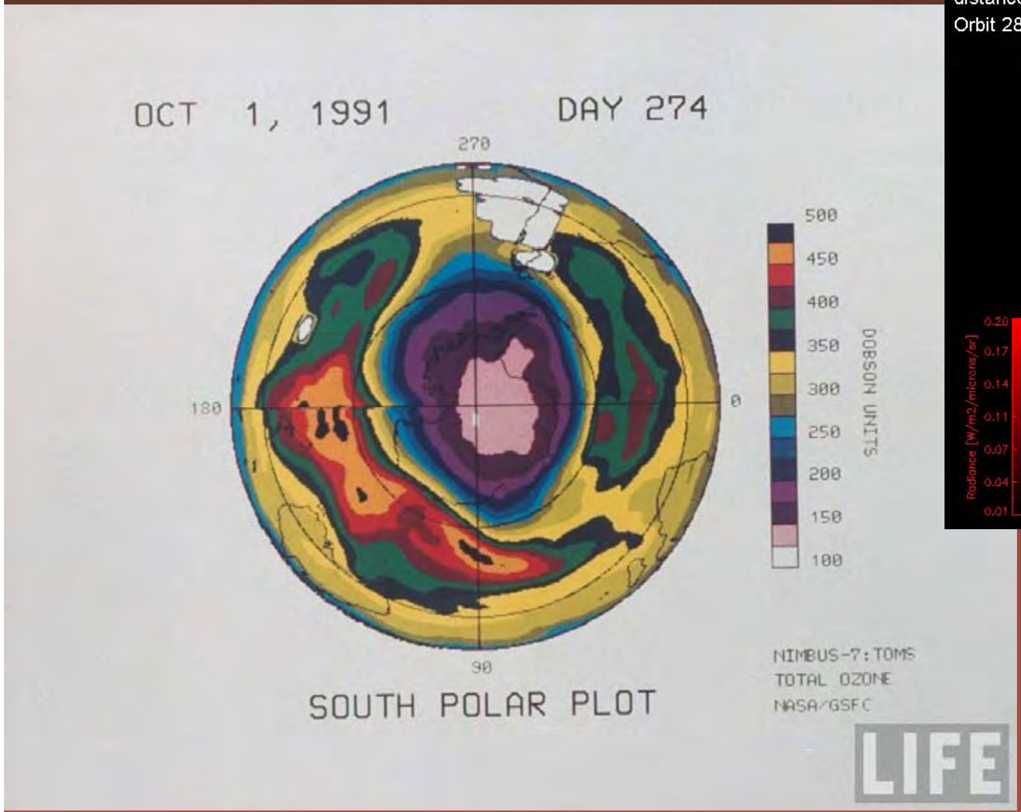
1 μm emission maps VIRTIS/VEX

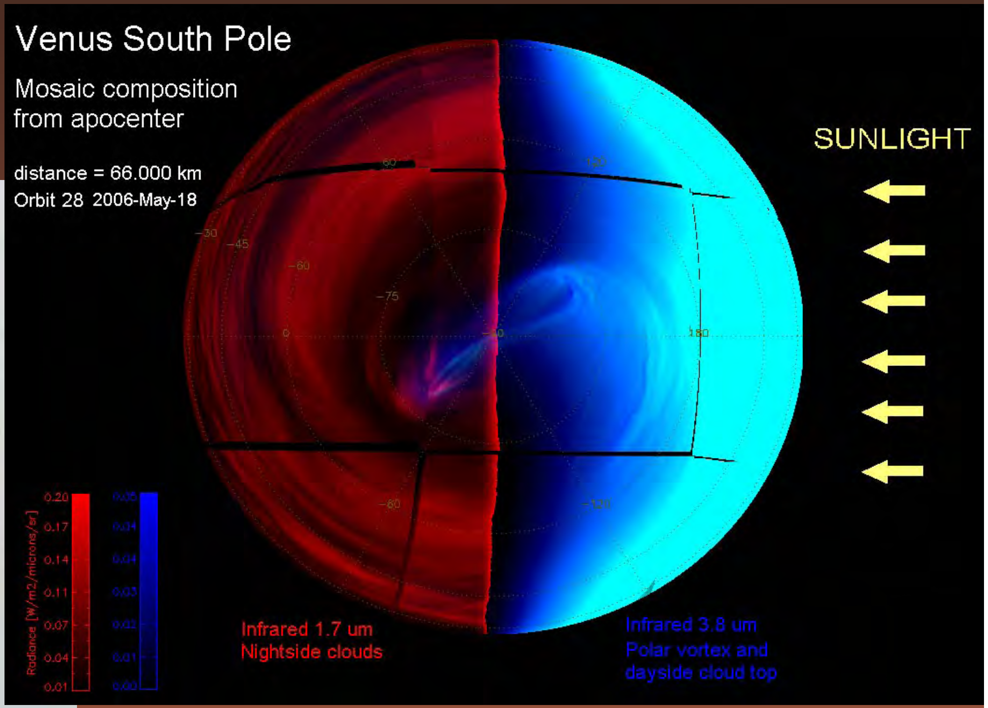


1 μm emission maps, temperature removed

Learning about Earth by Studying Venus

Prediction of O_3 loss due to CFCs followed directly from studying Venus atmospheric chemistry. TOMS below (Earth)





South polar vortex of Venus exhibits instability and ways to test Earth atmosphere dynamics VEX (left IR emission, right solar reflection)

Venus Flagship Science Objectives

Venus Flagship Science Objectives

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

Main resources:

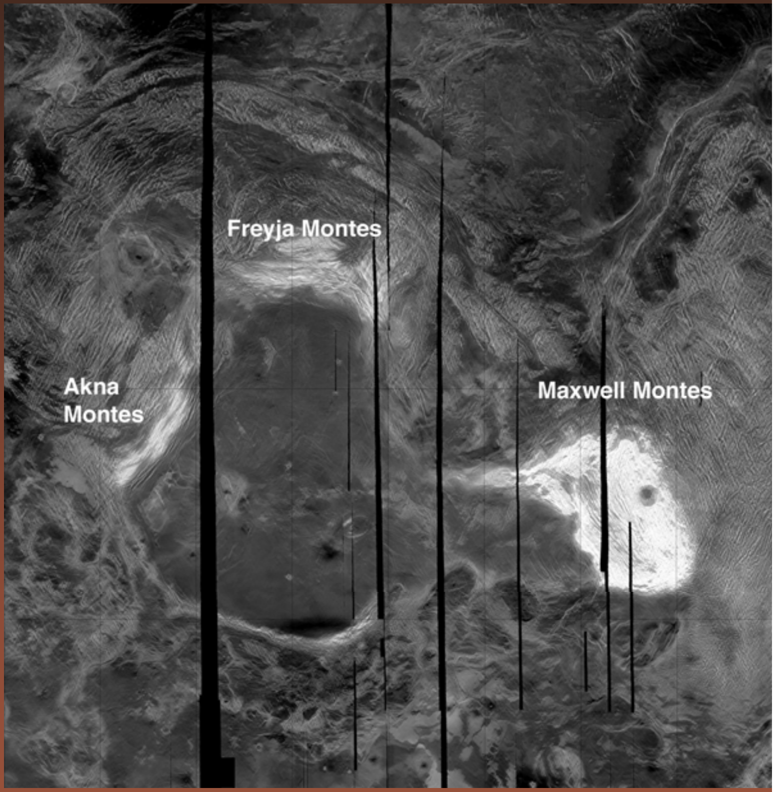
- 2003 Decadal Survey
- VEXAG 2007 report
- 2006 NASA Roadmap

Phase 1

Mission Architecture Trade Study

- STDT & JPL Team assessed the mission architecture trade space:
  - Identified 13 architectural elements
    - e.g. orbiter, landers, balloons, probes
  - Targeting various altitude regimes
    - from surface to low/mid/high altitudes and orbit
  - Single and multiple elements were considered
    - e.g., networks, multi-probes
- These architecture elements assembled into 17 mission architectures
- Science FOMs and Technology Difficulty used to select highest value science architecture within design constraints

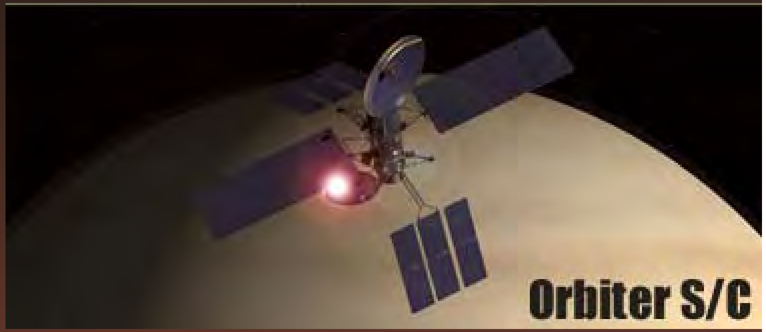
Magellan - Ishtar Terra

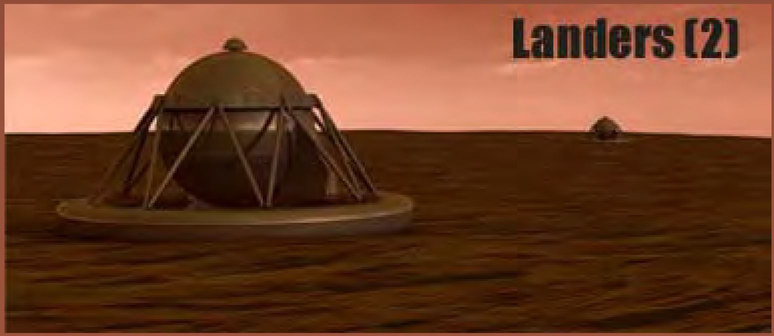


The Design Reference Mission
(Animation)

Design Reference Mission

- The DRM requires a dual-launch approach using a pair of Atlas 551 rockets:
  - 1 orbiter, arrives first to serve as telecom relay
  - 1 carrier, arrives second, with 2 entry vehicles, each with a balloon and a lander, delivered into the atmosphere 13 hours apart
  - Launches in 2021, arrivals in 2022
  - Orbiter serves as a telecom relay for landers (5 hours) and balloons (30 days)
  - 2 year radar mapping science mission after aerobraking to a 230 km circular orbit
- The balloons and landers communicate through the orbiter, with the carrier serving as a limited emergency backup
- The lander sites are Alpha Regio (-27°, 3° E) and the lava flows at -47.4°, 6.5° E
  - The balloons are expected to circumnavigate Venus 5-7 times and drift poleward
- A complete instrument list that serves as the planning payload is given on the next slide.



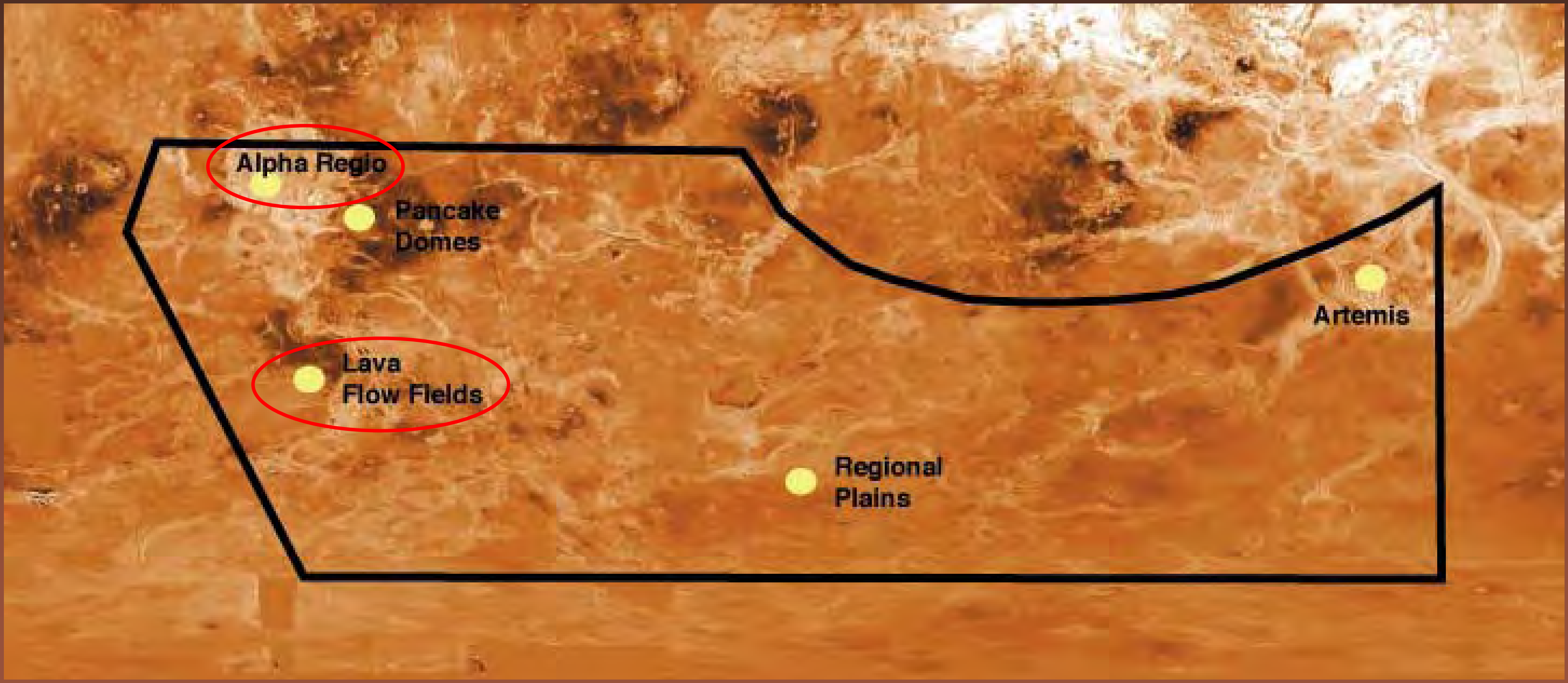


DRM Planning Payload

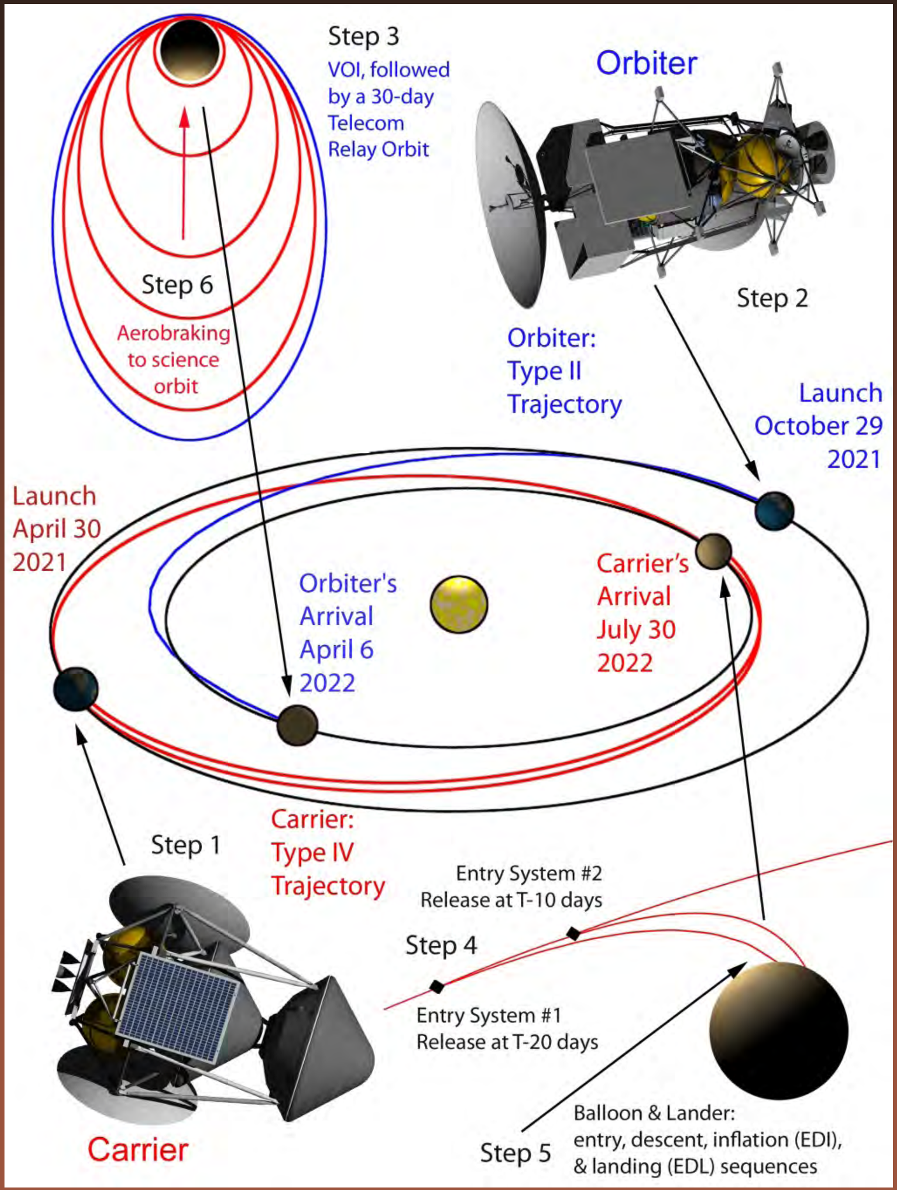
Orbiter	2 Balloons	2 Landers	
Lifetime (4 years)	(1 month)	Descent Phase (1–1.5 hour)	Landed Phase (5 hours)
InSAR — Interferometric Synthetic Aperture Radar	ASI — Atmospheric Science Instrument (pressure, temperature, wind speed.)	ASI	Microscopic imager
Vis–NIR Imaging Spectrometer	GC/MS — Gas Chromatograph / Mass Spectrometer	Vis–NIR Cameras with spot spectrometry	XRD / XRF
Neutral Ion Mass Spectrometer	Nephelometer	GC / MS	Heat Flux Plate
Sub–mm Sounder	Vis-NIR camera	Magnetometer	Passive Gamma Ray Detector
Magnetometer	Magnetometer	Net Flux Radiometer	Sample acquisition, transfer, and preparation
Langmuir Probe	Radio tracking	Nephelometer	Drill to ~10 cm
Radio Subsystem (USO — Ultra Stable Oscillator)			Microwave corner reflector

DRM Lander Sites

- Of the five candidate sites located within the reachable area (black border), the STDT selected the two landing sites circled in **red**.

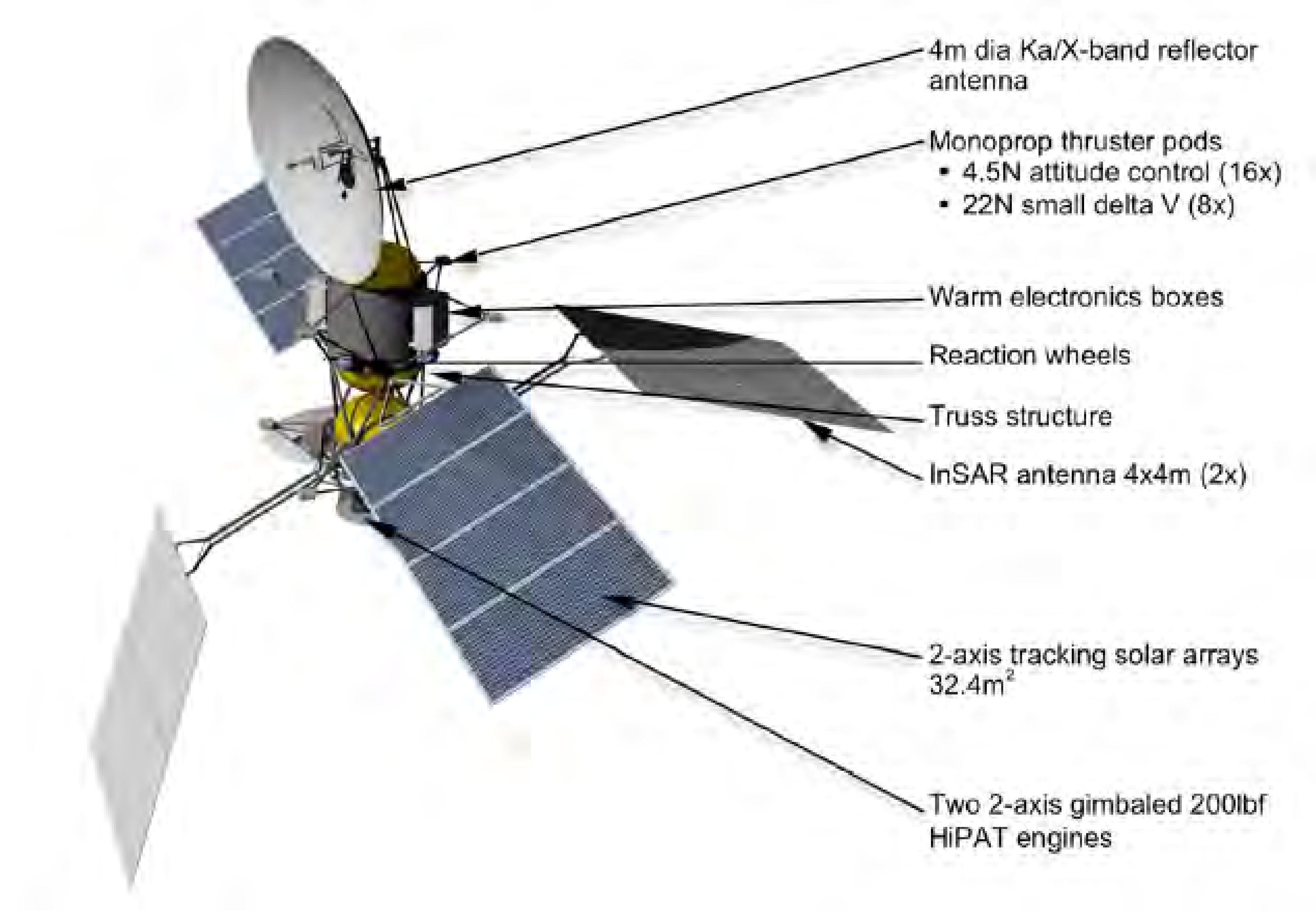


Mission Design



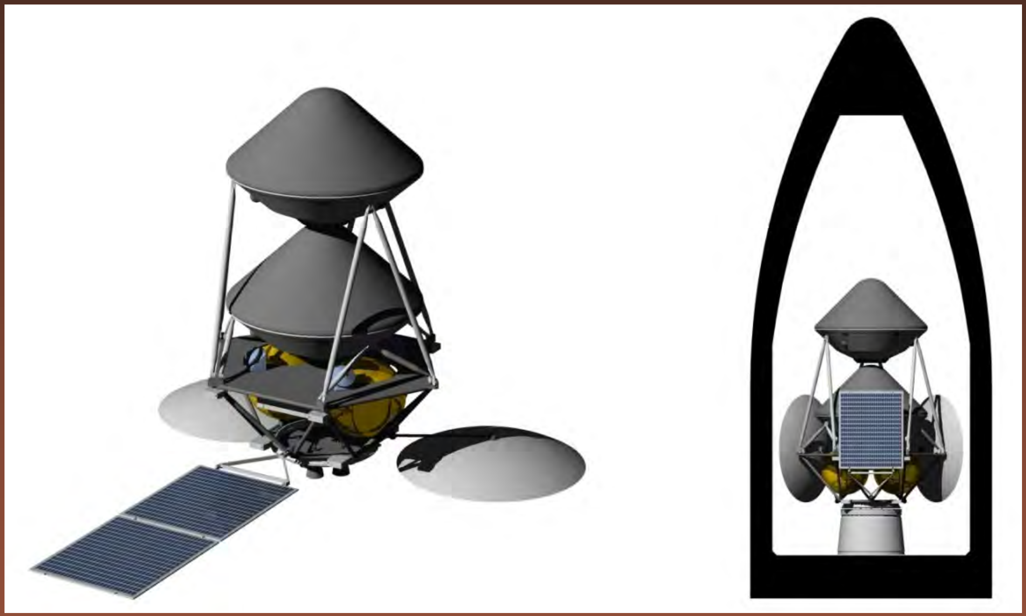
- Carrier with entry vehicles launches first, arrives second
- Orbiter launches second, arrives first and sets up to be a telecom relay in a 300 x 40000 km near polar orbit
- Entry vehicles arrive 13 hours apart so only 1 lander communicates with the orbiter at a time
- After 1 month of balloon mission, orbiter ends telecom support and aerobrakes down to a 230 km circular orbit for a 2 year science mission phase

Orbiter

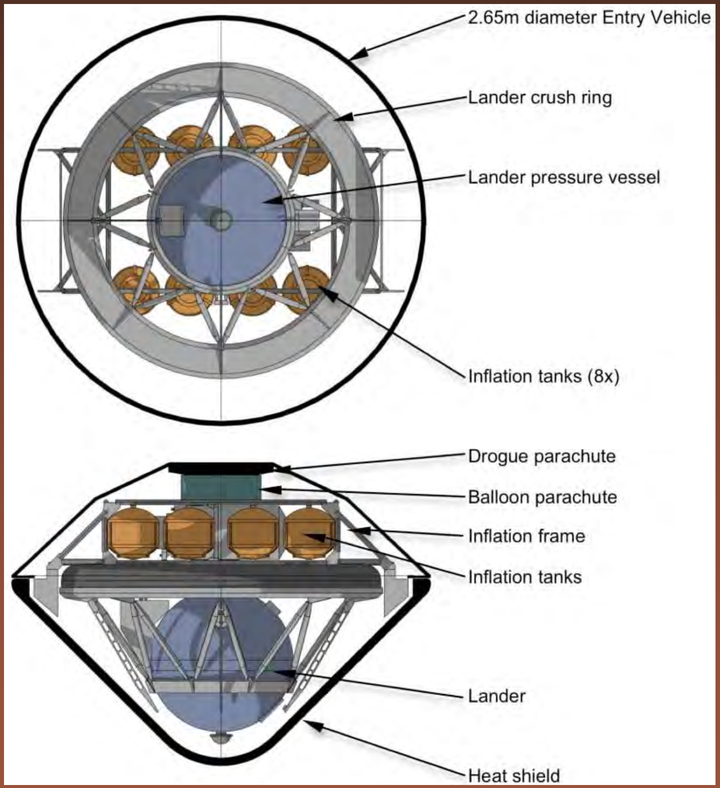

4m dia Ka/X-band reflector antenna
Monoprop thruster pods
• 4.5N attitude control (16x)
• 22N small delta V (8x)
Warm electronics boxes
Reaction wheels
Truss structure
InSAR antenna 4x4m (2x)
2-axis tracking solar arrays 32.4m²
Two 2-axis gimbaled 200lbf HiPAT engines

Carrier and Entry Vehicles

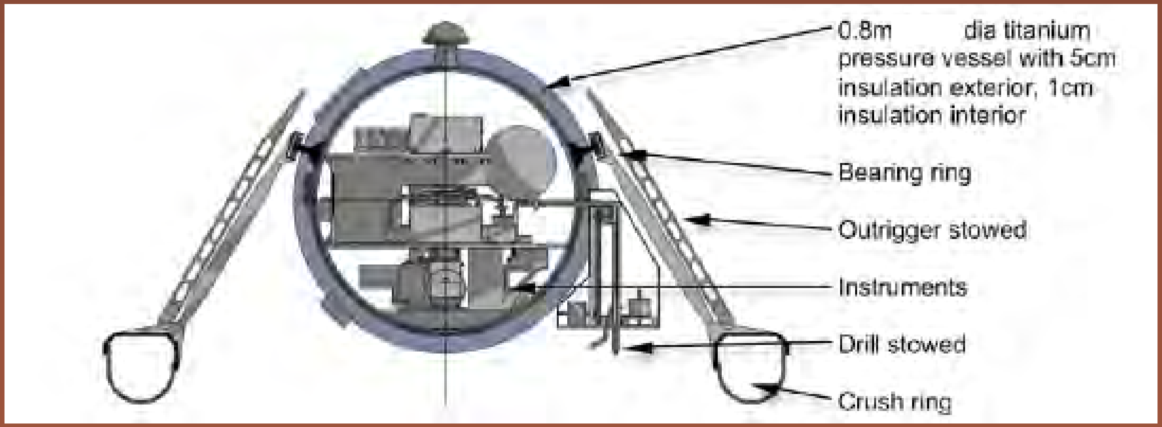
The carrier uses an inline stacked configuration for the entry vehicles. There is ample room inside the 4.5 m launch vehicle fairing.



The entry vehicles are PV and Galileo style 45º sphere cone aeroshells, sized at 2.65 m diameter to accommodate all internal components.

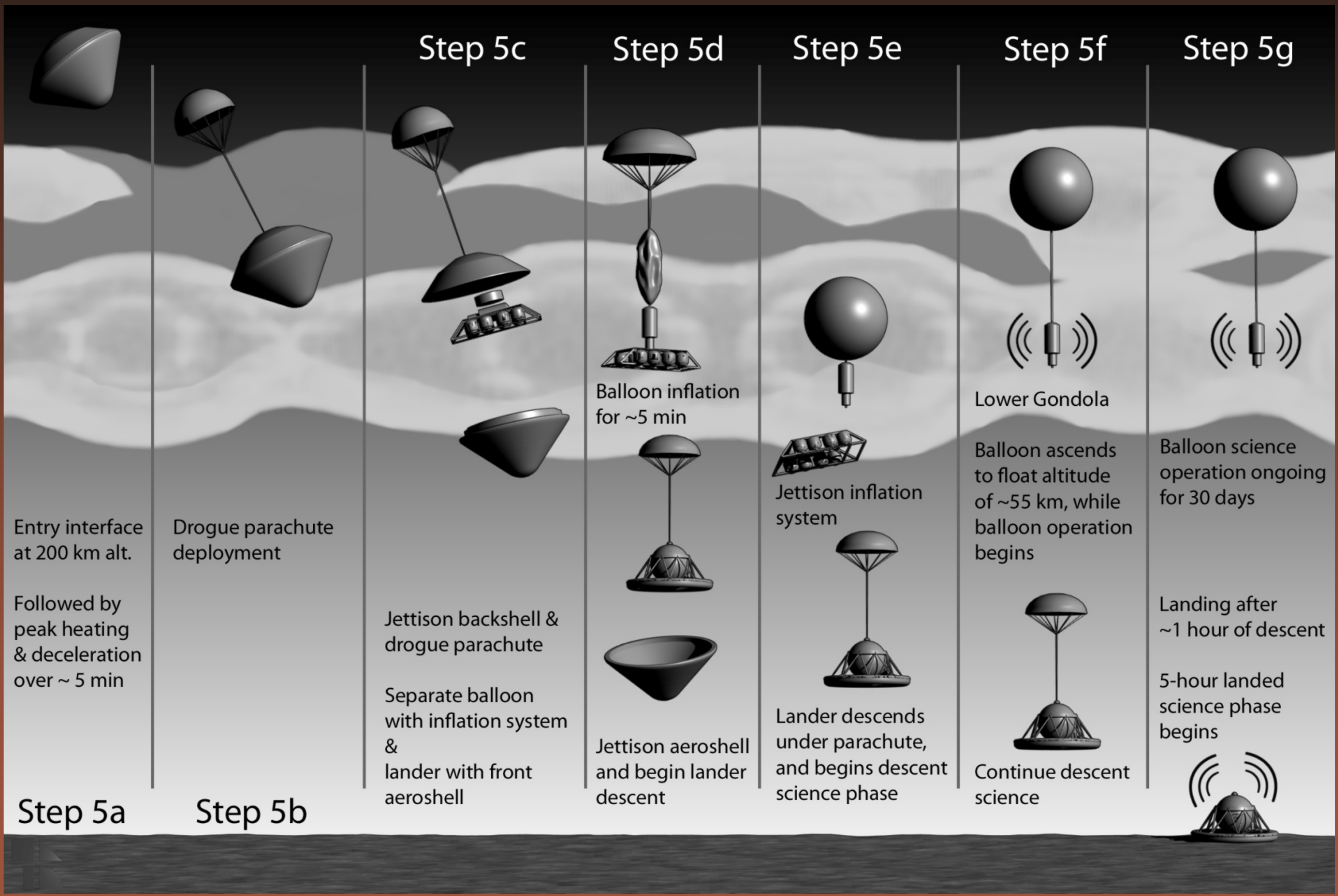


Landers and Balloons



5.5 m prototype superpressure balloon (JPL/ILC Dover/NASA Wallops)

Entry, Descent and Landing (Inflation)



Launch Mass Summary

- Each of the two launch vehicles in our architecture needed to be the largest Atlas V available (Atlas 551):

- Orbiter:
  - Dry Mass (CBE) = 1591 kg
  - Margin (43%) = 684 kg
  - Propellant = 3030 kg
  - Total = 5305 kg

  - LV capability = 5450 kg
  - LV Margin = 2.6%

- Carrier & In situ vehicles:
  - Carrier (CBE) = 781 kg
  - Entry Vehicles (2) CBE = 1566 kg
  - Landers (2) CBE = 962 kg
  - Balloons (2) CBE = 209 kg
  - Helium CBE = 26 kg
  - Margin (43%) = 1511 kg
  - Propellant = 523 kg
  - Total = 5578 kg

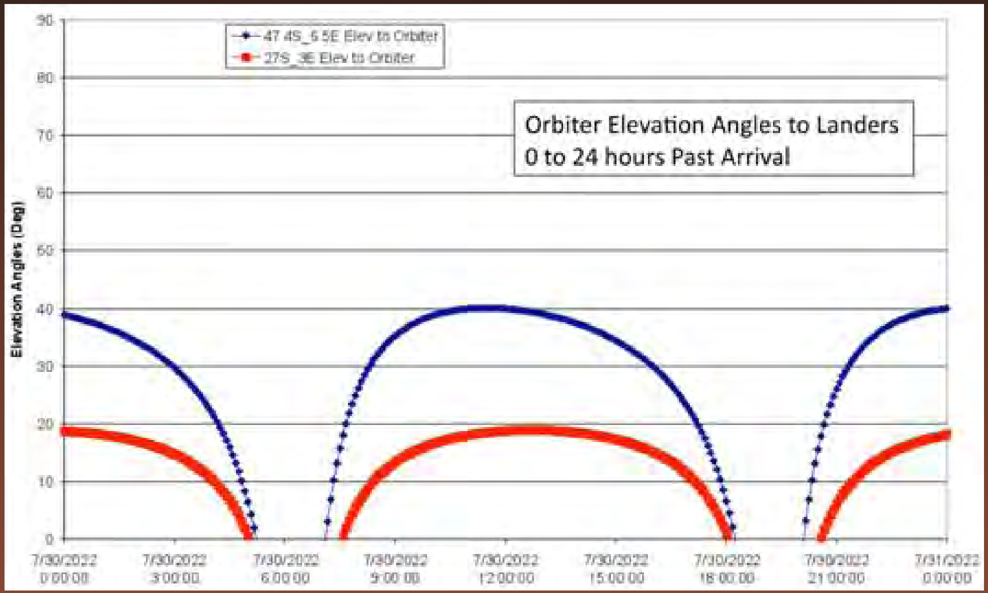
  - LV capability = 5580 kg
  - LV Margin = 0%

Data Volume Summary

- Preliminary data collection budgets were developed for all of the instruments on all of the platforms.
  - Orbiter (300 Tbits):
    - InSAR instrument provides ~99.99% of all orbiter data
  - Lander (1 Gbit each):
    - Panoramic imaging: 590 Mbits (59%)
    - Descent imaging: 200 Mbits (20%)
    - XRD/XRF: 140 Mbits (14%)
  - Balloon (21 Mbit each):
    - VASI + nephelometer: 18 Mbits (86%)
    - GCMS: 1.6 Mbits (8%)
    - Microphone 0.7 Mbits (3%)
- The data collection strategy is different for each platform:
  - Orbiter data is collected throughout the 2 year main science mission
  - Lander data is collected continuously during the 1 hour descent and 5 hour surface mission.
  - Balloon data is collected over 30 days, with significant duty-cycling to conserve electrical power.

Telecom Strategy

- The orbiter will serve as a telecom relay for the landers and balloons during the first part of the mission.
- The 300 by 40000 km initial orbit is oriented with the apoapse over the lander sites to maximize temporal coverage
- Analysis shows (see graph at right) that 6 hour+ periods of visibility (> 15º above horizon) are provided for both landing sites



- The orbiter has a 2.5 m S-band antenna for lander and balloon communications
  - It uses redundant cross-strapped Electra transceivers.
- The orbiter has a 4 m dual-feed X- and Ka-band antenna for Earth comm
  - It uses redundant cross-strapped X-Ka Small Deep Space Transponders with redundant cross-strapped 200 W Ka-band 100 W X-band TWTAs
- The orbiter will use aerobraking to transition to the 230 km circular science orbit after the 1 month balloon mission ends.

Primary Issues and Risks

- Sample acquisition and handling
  - Venera/VEGA heritage is dated, improved capabilities likely will be required.
- Lander design and technologies
  - Require design for safe landing on rough terrain (tessera). Rotating pressure vessel concept requires development and validation.
- Launch vehicle limits
  - Atlas 551 limit already reached with 43% margin on CBE. Further mass growth will require descopes or much more expensive launch vehicles.
- Orbiter failure risk
  - Carrier can provide only a limited backup telecom capability if the orbiter fails. Are there better architecture options?
- System engineering complexity
  - The multi-element architecture is complex and few system engineering details have been worked out so far.
- Cost estimation uncertainties
  - Lack of experience and existing facilities makes it difficult to estimate costs for high temperature and high pressure V&V of lander and exposed instruments.

DRM Cost Estimates

- The JPL cost-complexity model (Peterson et al, 2008) gave a $2.7B estimate for the Design Reference Mission
  - The stated accuracy of this model ~40% on absolute cost, implying a maximum possible cost of $3.8B.
- The JPL study team created a second cost estimate that fused three sources: JPL's Team X cost models, study team expert inputs and a cost risk subfactor analysis to determined a recommended reserve level. The result is:

Element	Cost ($M)
Spacecraft CBE from Team X	1954
Additional PSE costs	30
Cost Reserves on CBE (41%)	813
Two Atlas 551 launch vehicles	445
Additional Technology Development Costs	107
Total	**3349**

- This cost is $3.35B, which is within the uncertainty range of the cost-complexity model.
- The final report lists a cost range of $2.7B to $3.8B for the DRM

Technology Challenges

Outline

•Technologies needed for implementation of current Design Reference Mission architecture and design

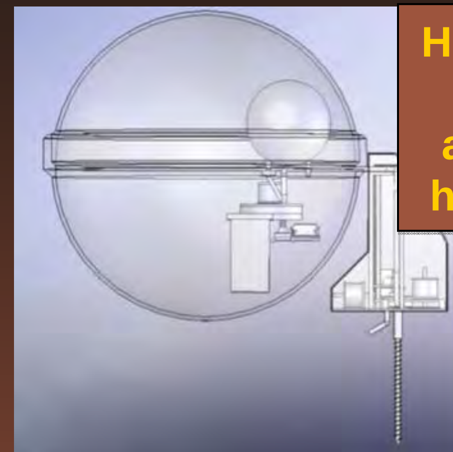
•Technologies for enhancements to DRM architecture and design

•Technologies for enabling new surface science – alternate mission architectures

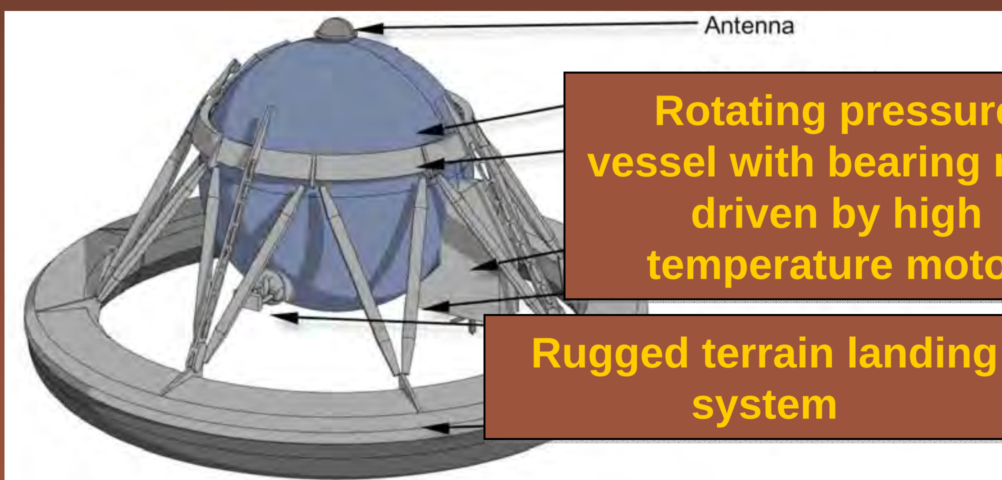
•Technology development priorities

Technology Development for DRM

Venus-like environment chamber for testing materials, components, instruments, and subsystems (and landers)



High temperature sample acquisition and handling system



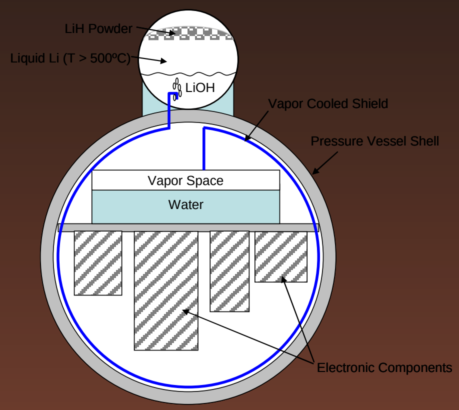
Rotating pressure vessel with bearing ring, driven by high temperature motor

Rugged terrain landing system

High temperature sensors and components for instruments operating and/or exposed to Venus environment

Moderate technology development is predominantly required for the landers.

Technologies for Enhancement of DRM



Water – Lithium getter Thermal Energy Storage System

Extension of the life of the lander from ~ 5hrs to ~24 hrs using advanced passive thermal control

Advanced passive thermal control options:

- Heat absorption system that utilizes the solid to liquid phase change and the liquid to vapor phase change of water in combination with Lithium Nitrate Phase Change Material (PCM).
- Evaporation of water using heat generated by the electronics and by vessel's parasitic heat loads and absorption of vapor by external water-getter such as Lithium metal
- Increase the heat storage capacity of the pressure vessel using an enclosed layer of lithium

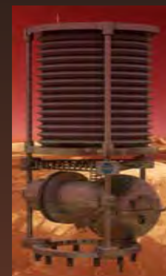
Replace primary battery based power system with Advanced Stirling Radioisotope Generator (ASRG) power source (or solar cells) to increase balloons mission life and data rate

- Data rate increase: 7x from balloon to Earth and 3x from balloon to orbiter vs current DRM design (primary batteries)
- Duration of the balloon mission no longer limited by primary batteries (1 month) but only by the lifetime of the super–pressure balloon

Surface Science New Capabilities

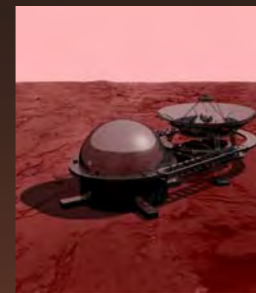
Seismometer and Meteorological Network

- Require long-lifetime measurements on the surface to
- Provide measurements of the size-frequency distribution of seismic events
- Surface meteorology with measurements such as temperature, wind speed and direction, and pressure
- Provide correlation between observed planetary events and changes in weather conditions



Low Altitude Balloons

- Multispectral imaging of surface at a resolution of 1–10 m
- Multiple surface analyses over different lithologies and chemical compositions correlated to those lithologies
- Extended traverse sampling, enabling the definition and correlation of large-scale geologic units



Long-Lived (months) Landers

- Sample multiple sites and multiple depths for a complete survey of the elemental composition, mineralogy, and chemistry of the landing site
- Acquire long-duration observations in time-varying phenomena like seismometry, meteorology, and wind
- Decrease mission risk and optimize science return by providing missions with complete instruments operation for extended period of time
- Humans in the loop during mission operation

Required technologies: Refrigeration, high temperature sensors and high temperature electronic components, balloon materials

Summary: Technology Priorities

	Technologies for DRM	Comments
1	Surface sample acquisition system and handling at Venus surface	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 in 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 lander operation on the surface of Venus is not possible unless lander life is extended to at least 24 hrs.

Design Reference Mission Science Performance

DRM Science Traceability- Themes to Observation Platforms

Science Theme	Science Objective	Instrument Type	Observation Platform
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	Vis-NIR Imaging Spectrometer	Orbiter
		Nephelometer	Balloon plus Lander (on descent)
		Net Flux Radiometer	Lander (on descent)
	Understand how superrotation and the general circulation work	Sub-millimeter Sounder	Orbiter
		Atmospheric Structure (P/T/winds/accel)	Balloon plus Lander (on descent)
		Radio (with USO)	Baloon
	Look for evidence of climate change at the surface	Vis-NIR Camera	Balloon plus Lander (on descent)
		Microscopic Imager	Lander
How active is Venus?	Identify evidence of current geologic activity and understand the geologic history	InSAR	Orbiter
	Understand how surface/atmosphere interactions affect rock chemistry and climate	GC/MS	Lander (on descent)
	Place constraints on the structure and dynamics of the interior	Radio (with USO)	Orbiter
		Magnetometer	Orbiter, Balloon, Lander
		Heat Flux Plate	Lander
		Corner Reflector	Lander
When and where did the water go?	Determine how the early atmosphere evolved	GC/MS	Balloon plus Lander (on descent)
		Langmuir Probe	Orbiter
		Neutral and Ion Mass Spectrometer (INMS)	Orbiter
	Identify chemical and isotopic signs of a past ocean	XRD/XRF	Lander
		Drill and sample acquisition, transfer and preparation	Lander
	Understand crustal composition differences and look for evidence of continent-like crust	Passive Gamma-ray Detector	Lander

Open Science Questions

The Atmosphere

MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS	DESIGN REFERENCE MISSION			
	Orbiter	Landers	Balloons	DRM with synergies
VENUS ATMOSPHERE				
How did Venus evolve to become so different from Earth?	Partial answer (yellow)	Major progress (green)	Will not answer (peach)	Major progress (green)
Was Venus ever habitable, and for how long?	Partial answer (yellow)	Major progress (green)	Will not answer (peach)	Major progress (green)
Did Venus lose a primary atmosphere due to impacts or loss to space?	Will not answer (peach)	Fully addresses (blue)	Fully addresses (blue)	Fully addresses (blue)
What drives Venus' atmospheric superrotation?	Major progress (green)	Partial answer (yellow)	Major progress (green)	Major progress (green)
How do geologic activity and chemical cycles affect the clouds and climate?	Partial answer (yellow)	Major progress (green)	Major progress (green)	Major progress (green)
How are atmospheric gases lost to space?	Major progress (green)	Partial answer (yellow)	Partial answer (yellow)	Major progress (green)

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

Open Science Questions

Geology

MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS	DESIGN REFERENCE MISSION			
	Orbiter	Landers	Balloons	DRM with synergies
VENUS GEOLOGY				
What is the volcanic and tectonic resurfacing history of Venus?	green	green	yellow	green
How were the heavily deformed highlands made?	yellow	green	yellow	green
How active is Venus geologically?	green	green	yellow	green
Did Venus ever have plate tectonics and if so, when did it cease?	yellow	yellow	yellow	green
How are geology and climate connected on Venus?	yellow	green	yellow	green
What has been the role of water and other volatiles in Venus geology?	yellow	green	yellow	green

blue	Fully addresses question
green	Major progress in answering the question
yellow	Partial answer to the questions
peach	Will not answer the questions

Open Science Questions

Interior Structure

MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS	DESIGN REFERENCE MISSION			
	Orbiter	Landers	Balloons	DRM with synergies
VENUS INTERIOR STRUCTURE				
Does Venus have Earth-like continents?				
What are the chemical, physical, and thermal conditions of the interior?				
How does mantle convection work on Venus?				
What is the size and physical state of the core?				
What is the structure of the Venus lithosphere?				
How have water and other volatiles affected Venus' interior evolution?				

Fully addresses question

Major progress in answering the question

Partial answer to the questions

Will not answer the questions

Open Science Questions

Geochemistry

MAJOR OPEN SCIENTIFIC QUESTIONS ABOUT VENUS	DESIGN REFERENCE MISSION			
	Orbiter	Landers	Balloons	DRM with synergies
VENUS GEOCHEMISTRY				
Was there ever an ocean on Venus, and if so, when and how did it disappear?				
What caused the resufacing of Venus over the past billion years?				
What is the nature of chemical interactions between surface and atmosphere?				
What are the tectonic forces behind Venus' volcanism?				
How were the rocks and soils of Venus formed?				
What do chemical differences of terrains say about the evolution of Venus?				

Fully addresses question

Major progress in answering the question

Partial answer to the questions

Will not answer the questions

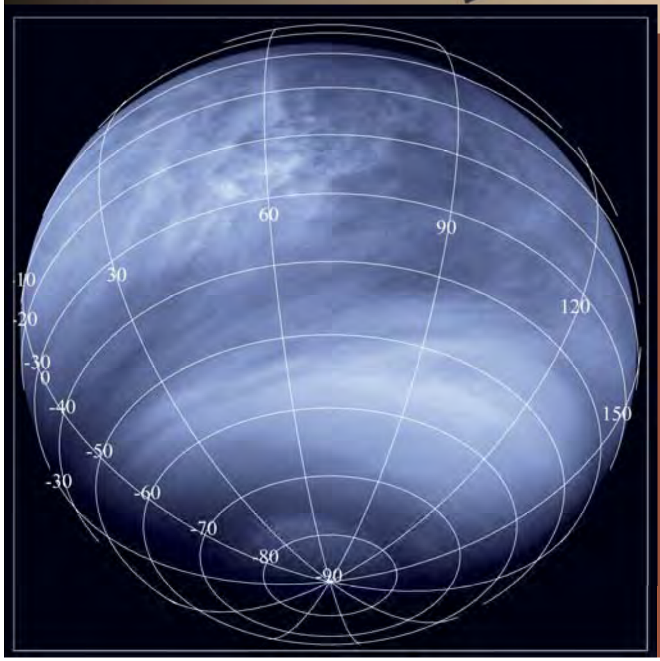
Recommendations for Future Work

Recommended Follow-on Study Topics

- Sample Acquisition and Handling System
  - Do a detailed design to understand more accurately the resource needs and technology development steps needed to meet the DRM objectives
- Lander Design
  - The rotating pressure vessel and rough terrain landing approach need detailed design to refine the resource requirements and scope the technology development plan
- Long-lived Seismometry and Meteorology
  - These were the top rated science investigations that were not included in the DRM. Detailed study is required to address the many questions concerning which technical approach will be most fruitful and what performance can be achieved.
- Humans-in-the-loop Lander Missions
  - Mission robustness will be improved if the lander lifetime can be extended long enough to enable meaningful humans-in-the-loop interactions. Detailed study is needed to quantify how much lifetime is required for different levels of interaction and the technological advances required to provide that lifetime.
- Near-surface Aerial Mobility
  - This was another very highly rated science investigation not included in the DRM. Detailed study is required to assess both refrigerated and non-refrigerated options.

Conclusions

Venus Flagship Orbital Science



- 5 m/pixel radar images in selected areas. 50 m globally
- Altimetry to 5 m vertically, 50 m horizontally
- Near–IR Mapping of the surface and 3-D mapping of the atmosphere
- Measurements of escaping gas species
- Magnetic field and lightning
- Detection of length of day changes

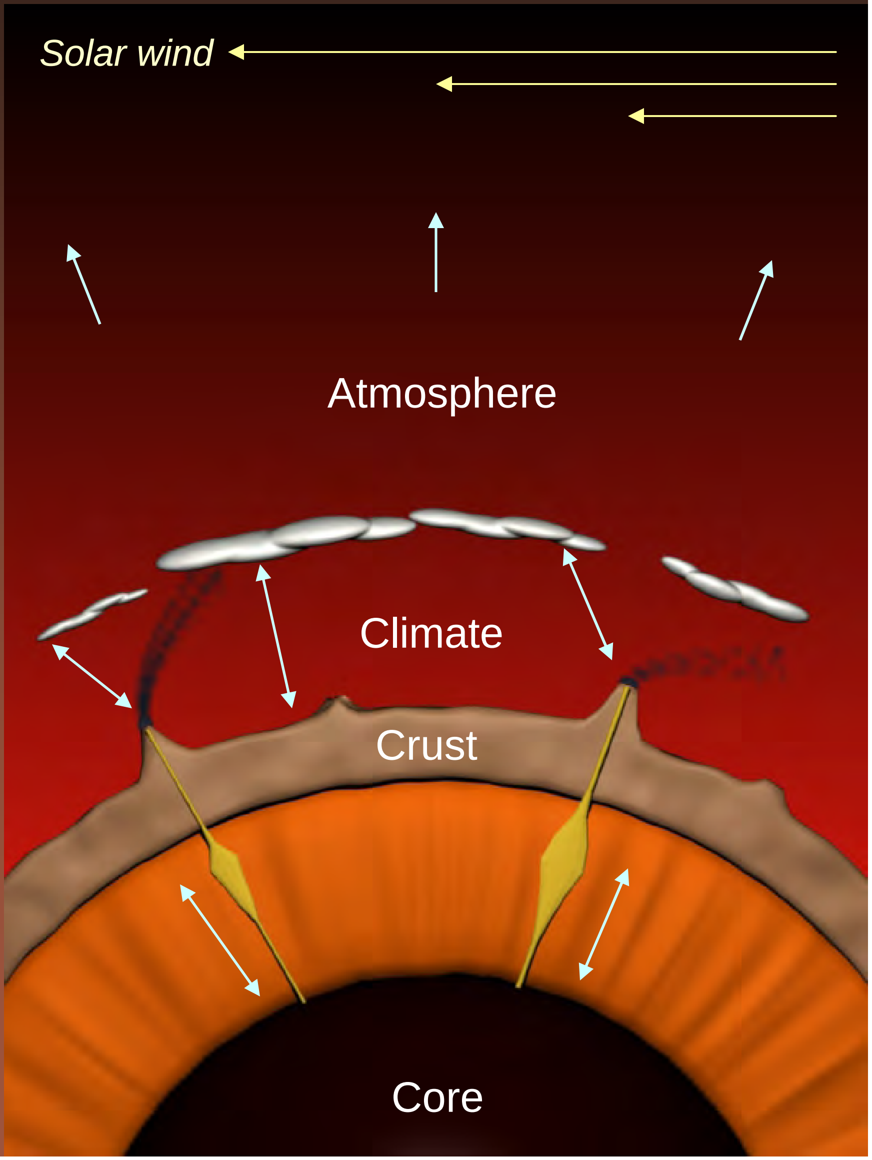
Venus Flagship In-Situ Science

- Winds, cloud chemistry and microphysics
- Noble gases
- Radiative energy balance

- Elemental & mineralogical analysis of rocks & soils
- Descent & panoramic imaging
- Deep atmosphere composition
- Corner reflector, heat flux

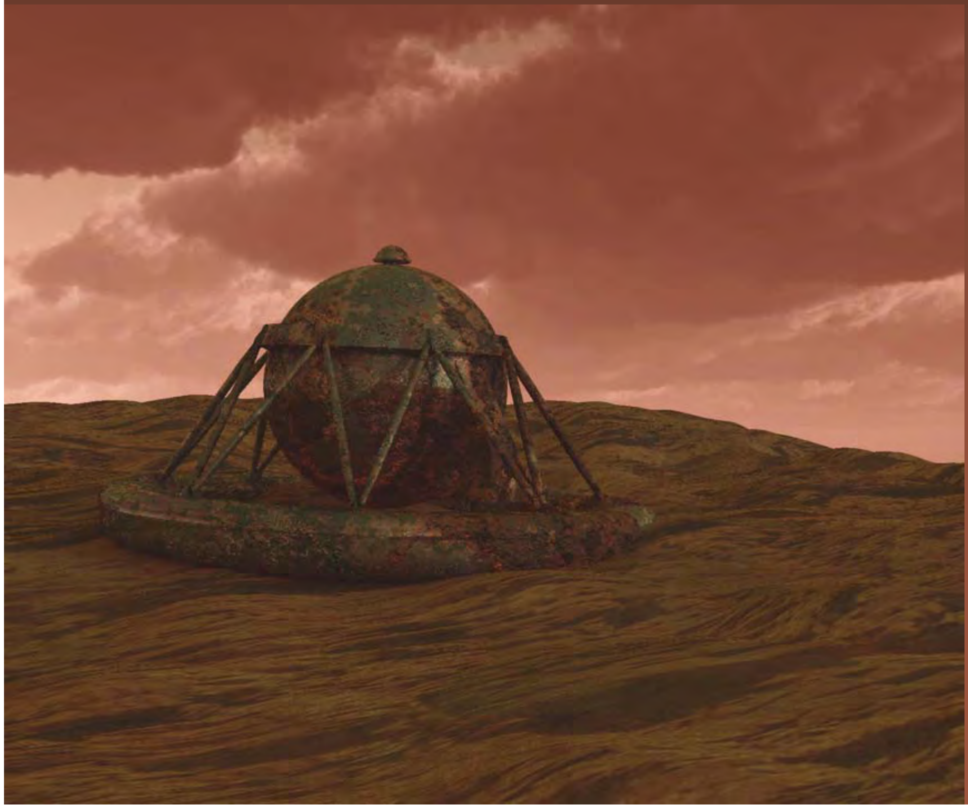
STDT Summary

- **What does the Venus greenhouse tell us about climate change?**
  - Probes through atmosphere simultaneously with balloons
  - Chemistry of the surface
- **How active is Venus?**
  - Highly capable orbiter with high resolution radar imaging, topography, and temporal changes
  - Geothermal heat flux
  - Near-IR images
- **When and where did the water go?**
  - Geochemistry and mineralogy at 2 locations on Venus
  - Atmospheric isotopes for early evolution
- A Venus Flagship mission in 2020-2025 can be done with moderate technology investment and relatively low risk.



Conclusions

- An orbiter, 2 balloons and 2 landers provide the highest science return.



- VFM studies Venus as an interconnected system – atmosphere, clouds, surface, and interior.
- VFM is a large NASA planetary mission with the explicit intention of better understanding our own world.