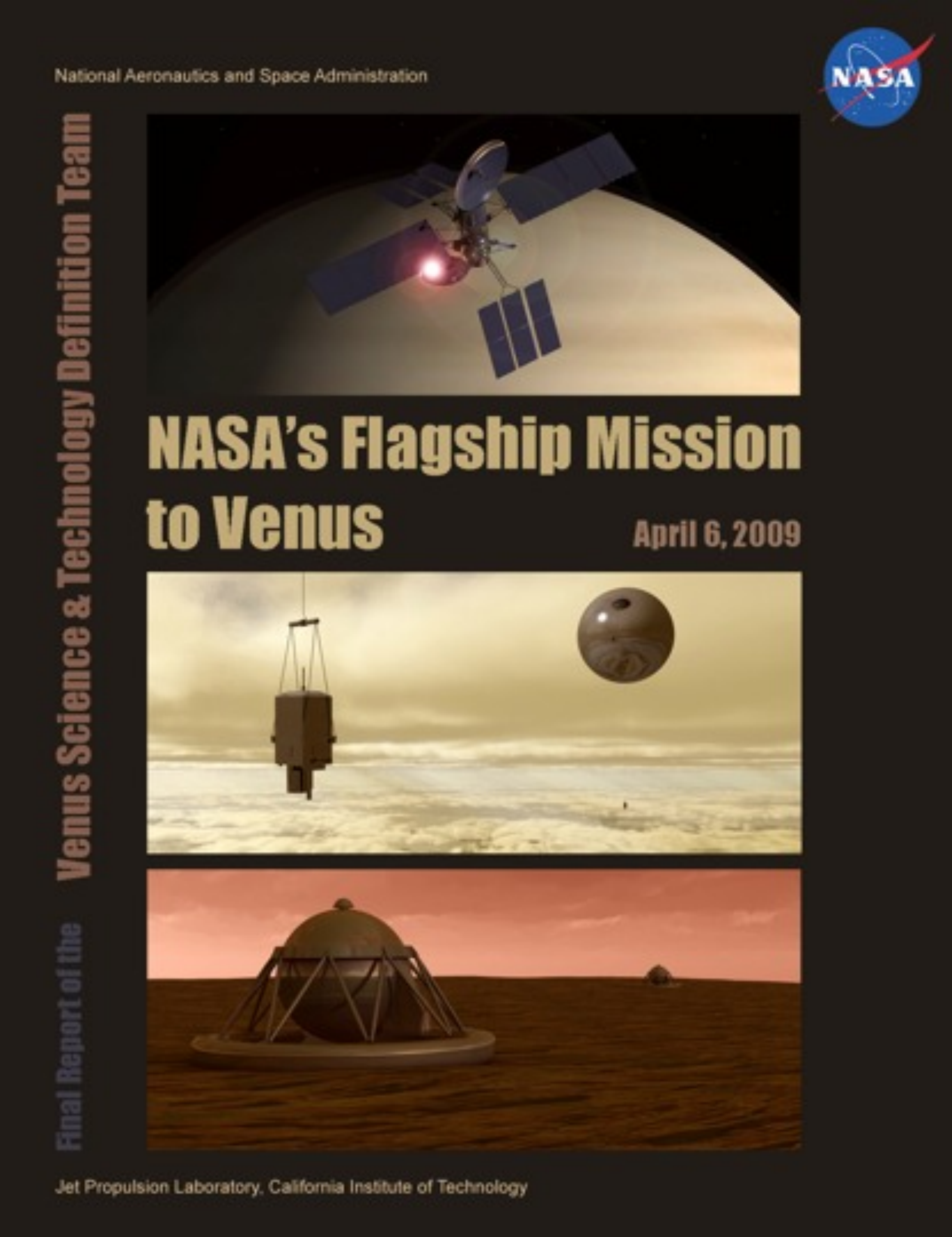


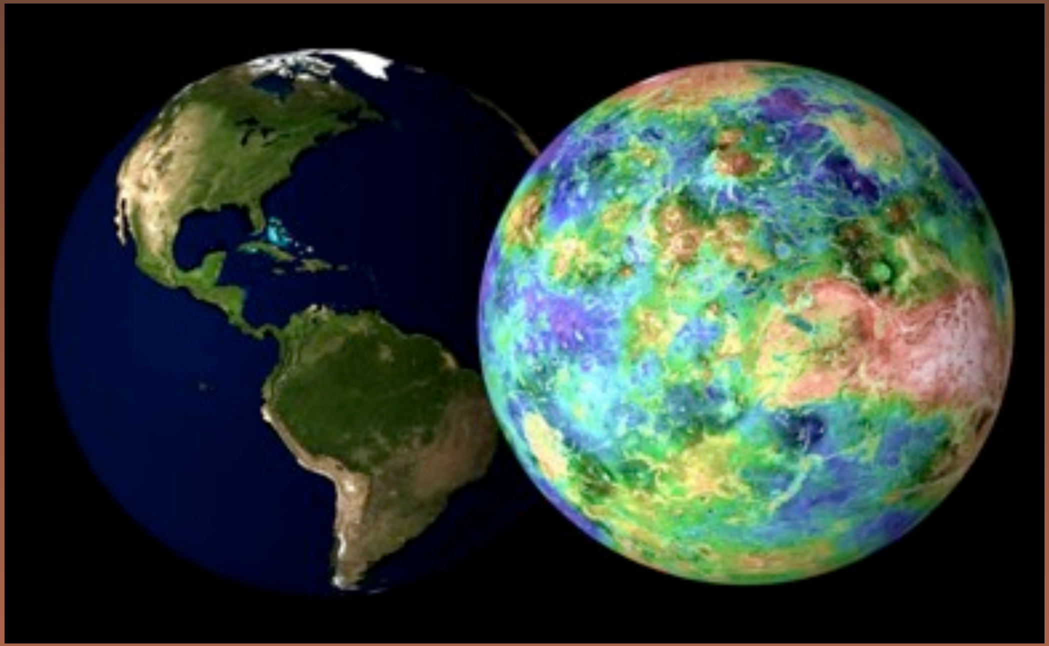
A Flagship Mission to Venus

Report of the Venus Science and Technology Definition Team

NASA HQ, April 6, 2009

Venus: Exploring a World of Contrasts

- The study of Venus has deepened and broadened our view of the Earth
- We will not be able to understand observations of terrestrial planets around other stars without understanding Venus.
- The formation and evolution of potentially habitable planets around other stars will require study of Earth, Mars, and Venus.



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 & Maturation Schedule
  - 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)
- **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:	≤ 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

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?

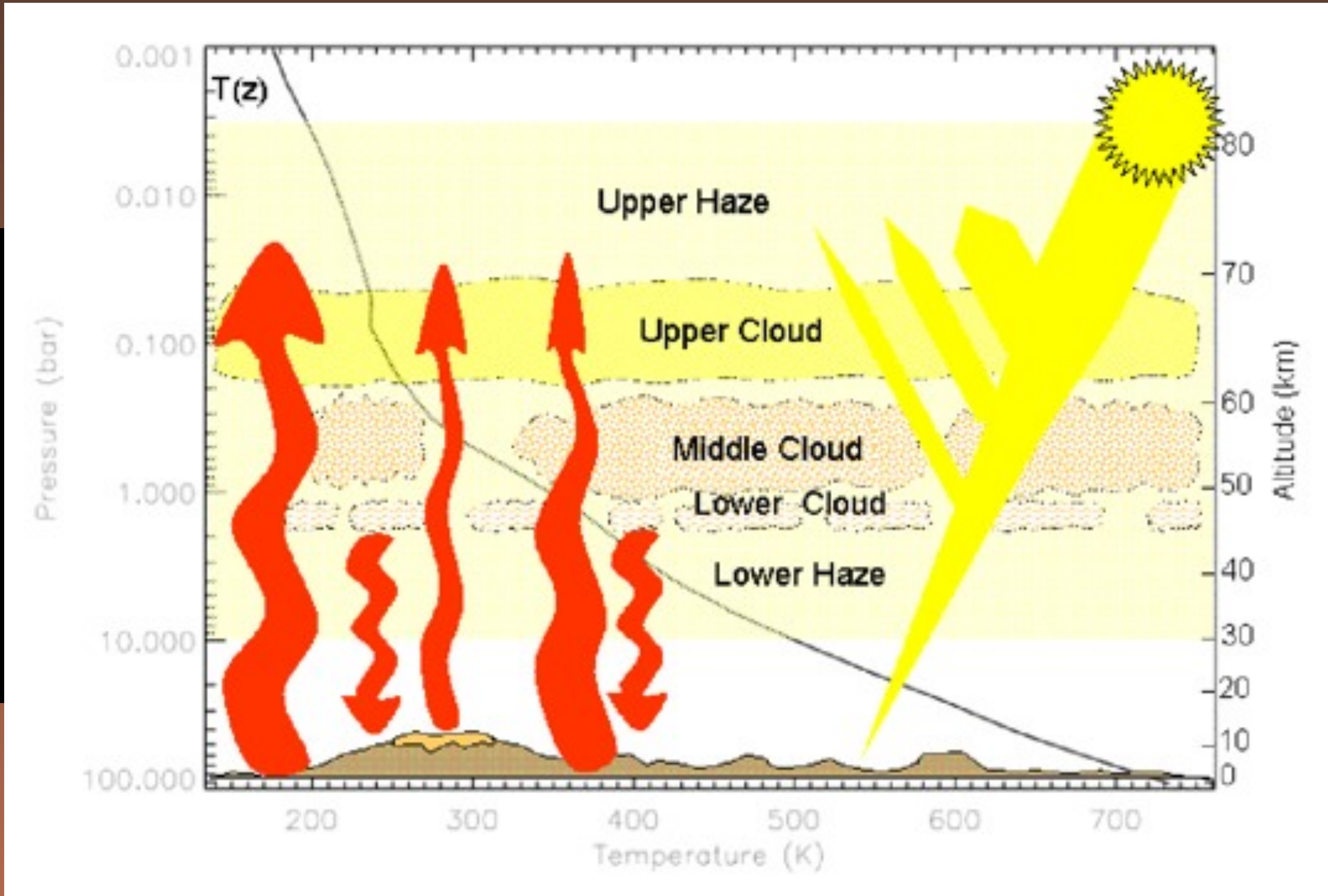
- How active is Venus?
  - Is Venus geologically active and what is it’s geologic history?
  - How do surface/atmosphere interactions affect rock mineralogy and climate?
  - What is structure of the interior, and what are its dynamics?

- 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?

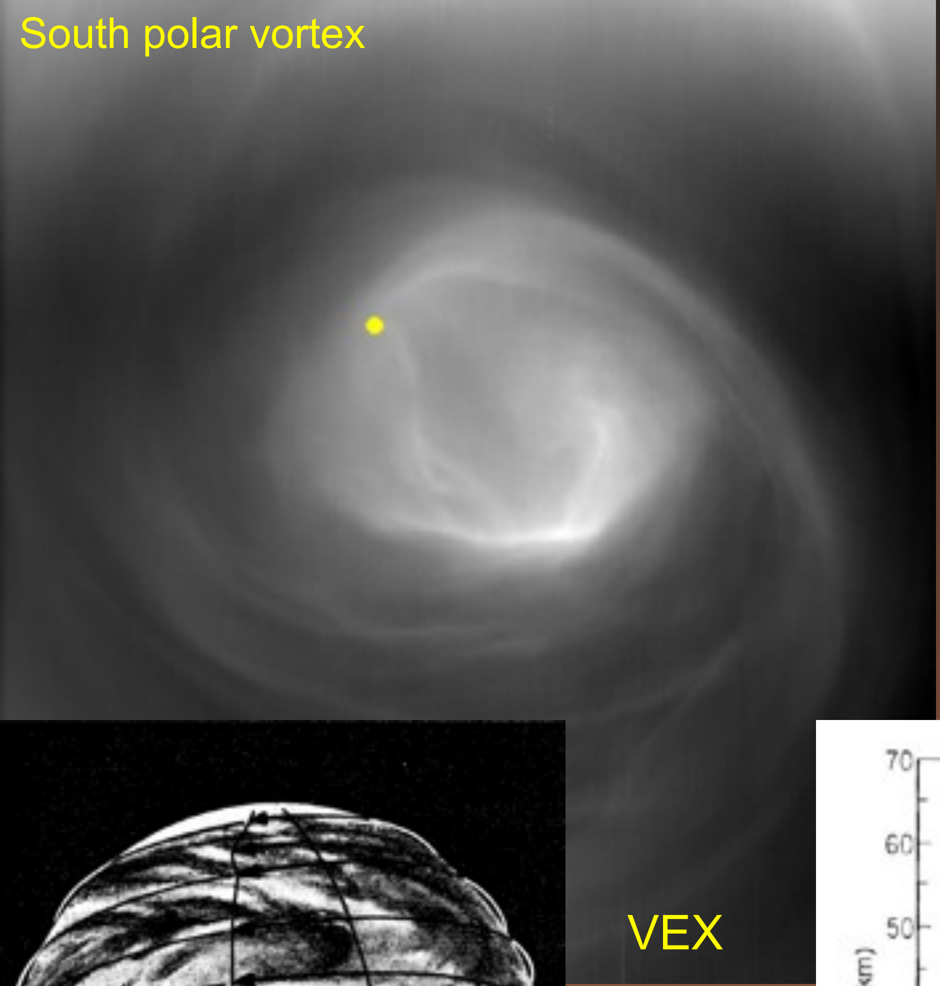
The Venus Greenhouse

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

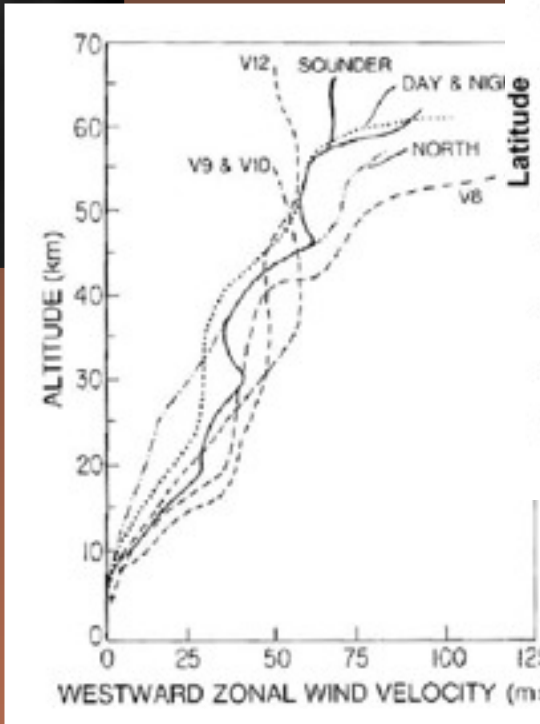
Mariner 10

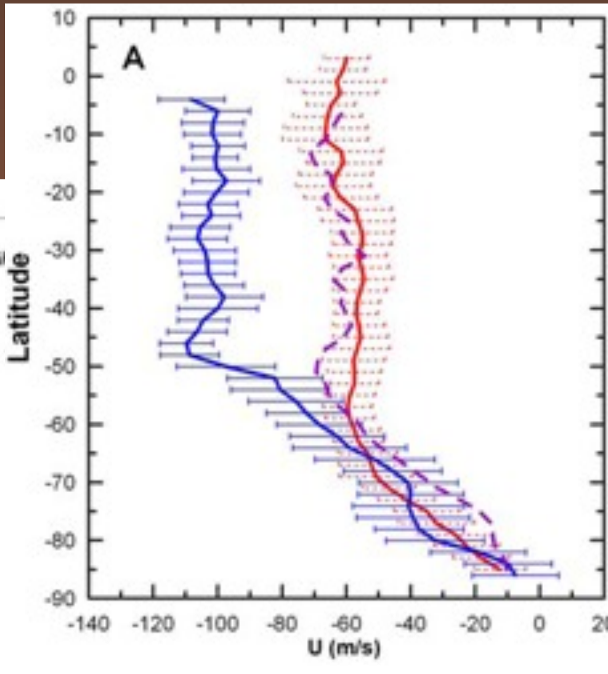


Why does the atmosphere superrotate?

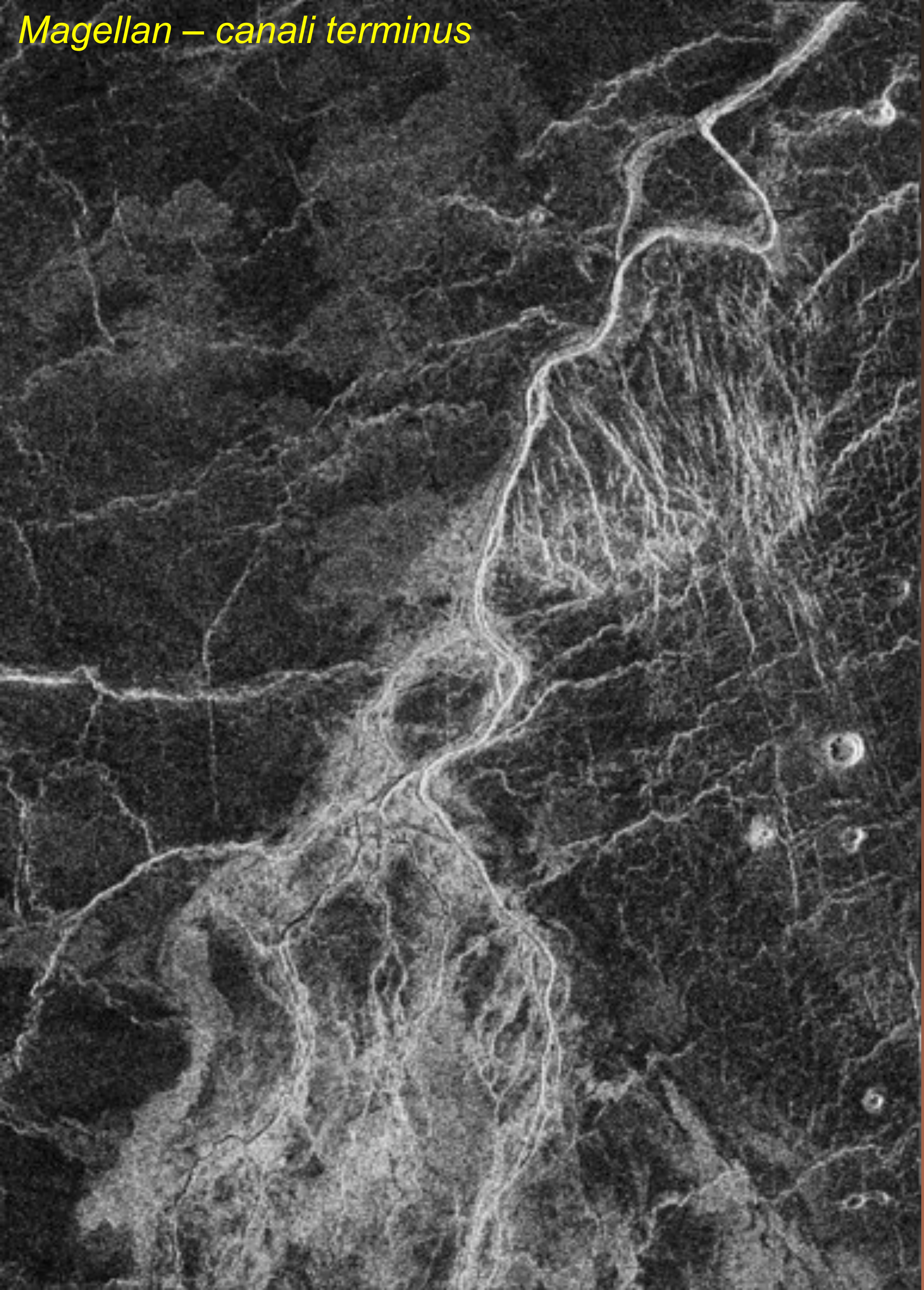


Probes: Winds decrease with altitude





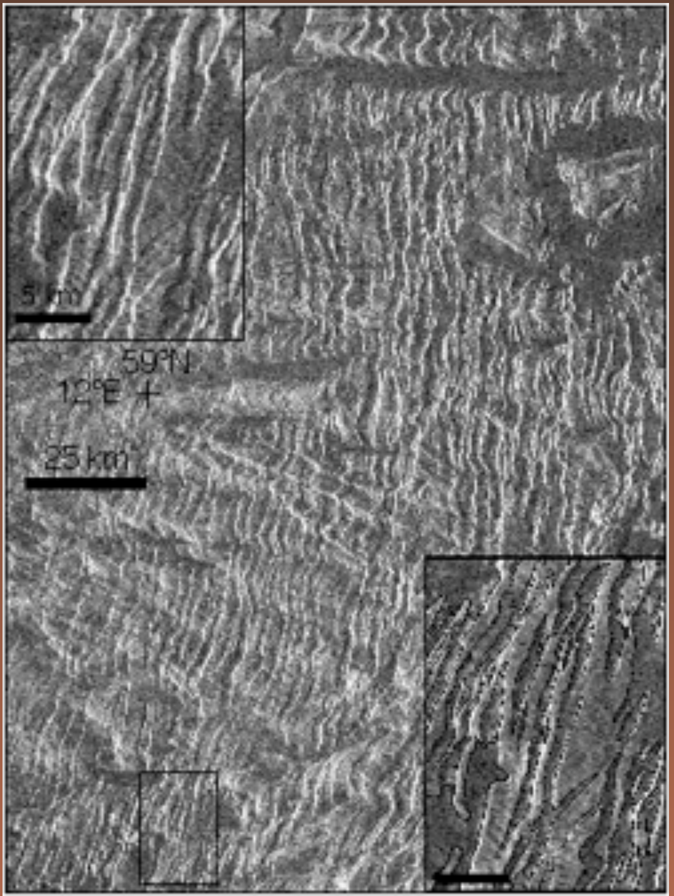
VEX East-west winds, decreasing at the poles



Magellan – canali terminus

Some surface features from Magellan hint at climate change

Magellan – Tessera terrain



Is there evidence for climate change at the surface?

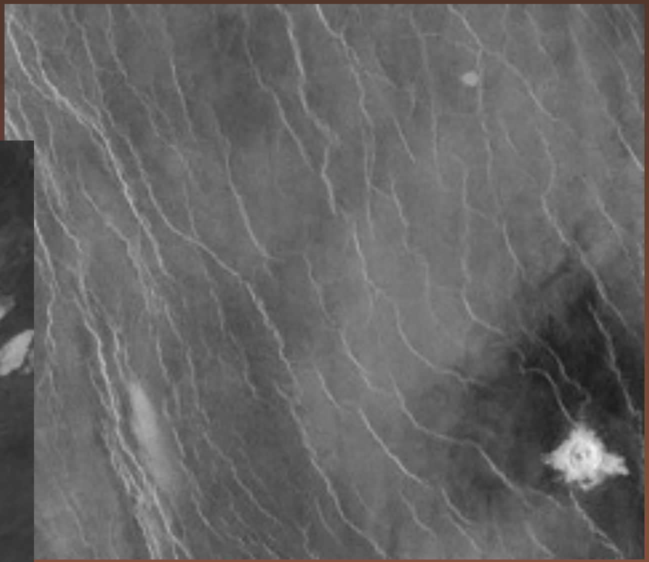
Processed Venera 13 panorama

Weathered rock may hold the chemical clues

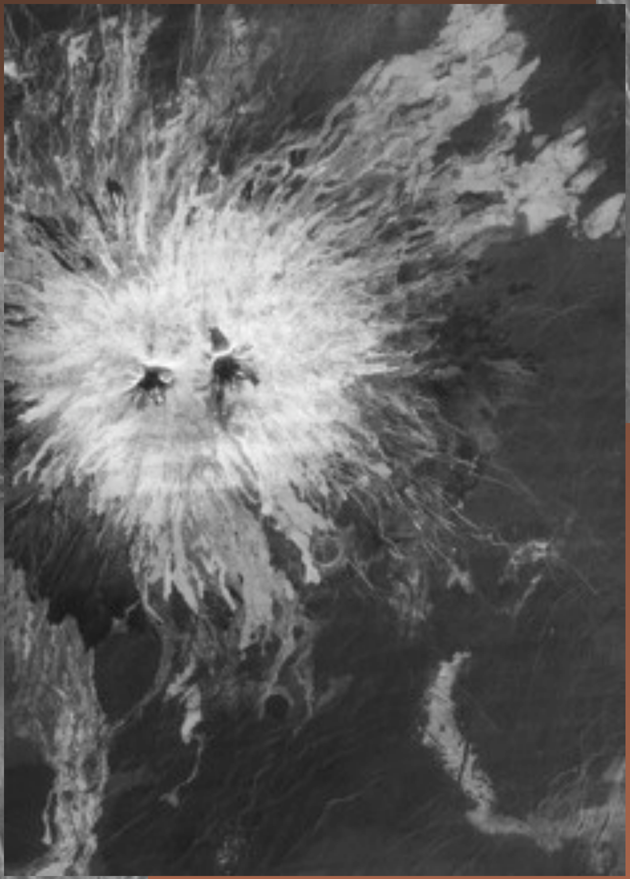
Is Venus Geologically Active?

Magellan saw young volcanic features

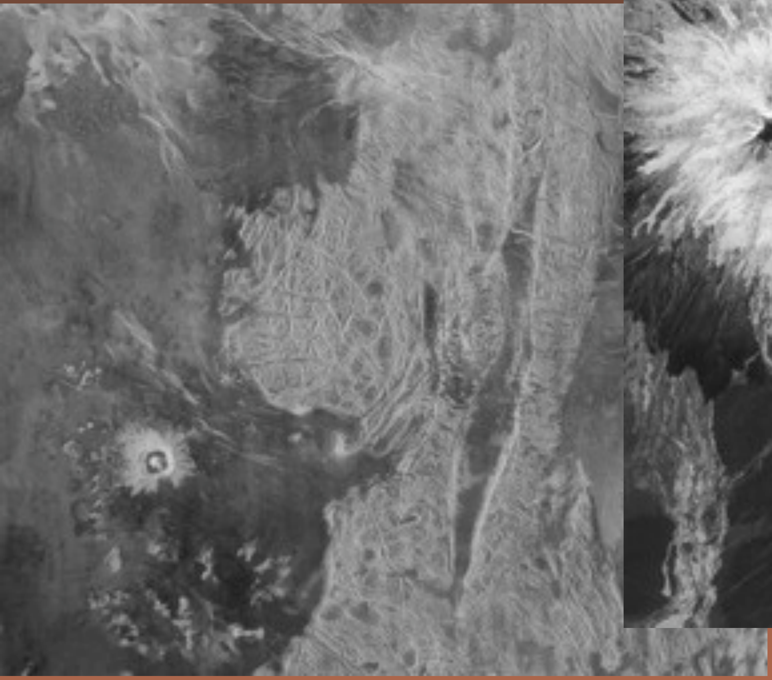
Plains



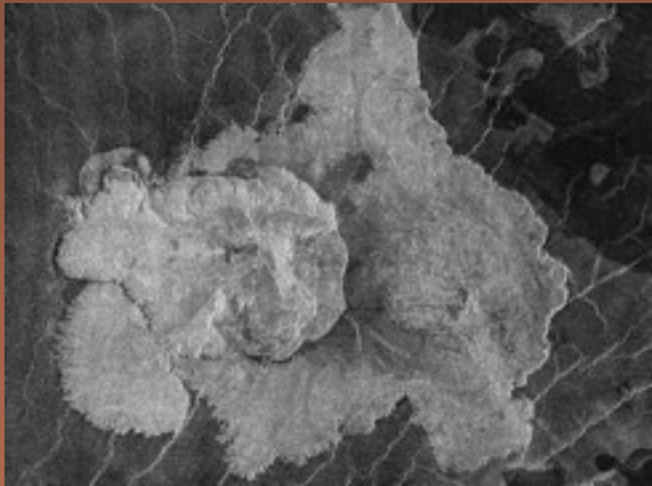
Volcanoes



Tessera

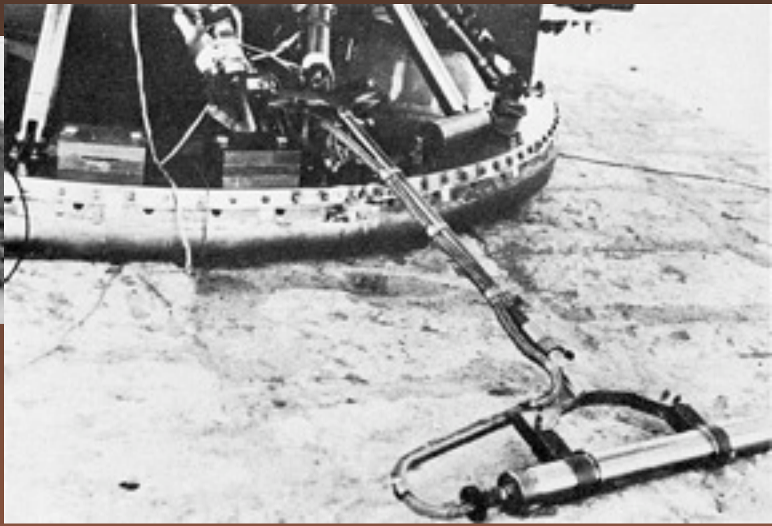


Compositional Diversity



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

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?

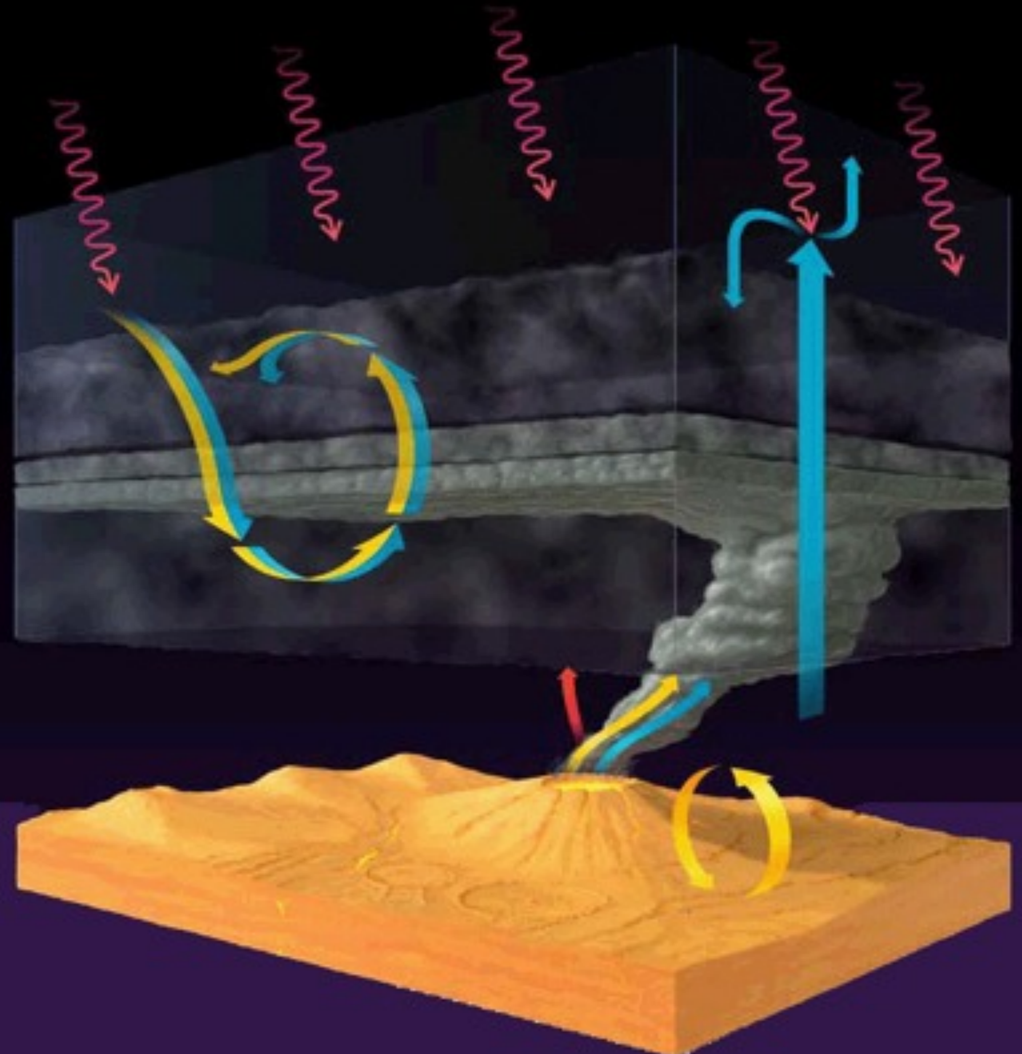
What destroyed the first 85% of Venus' surface history?

Geologic survey

Heat flux

Seismometry

How did early Venus evolve? Did it have oceans?



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

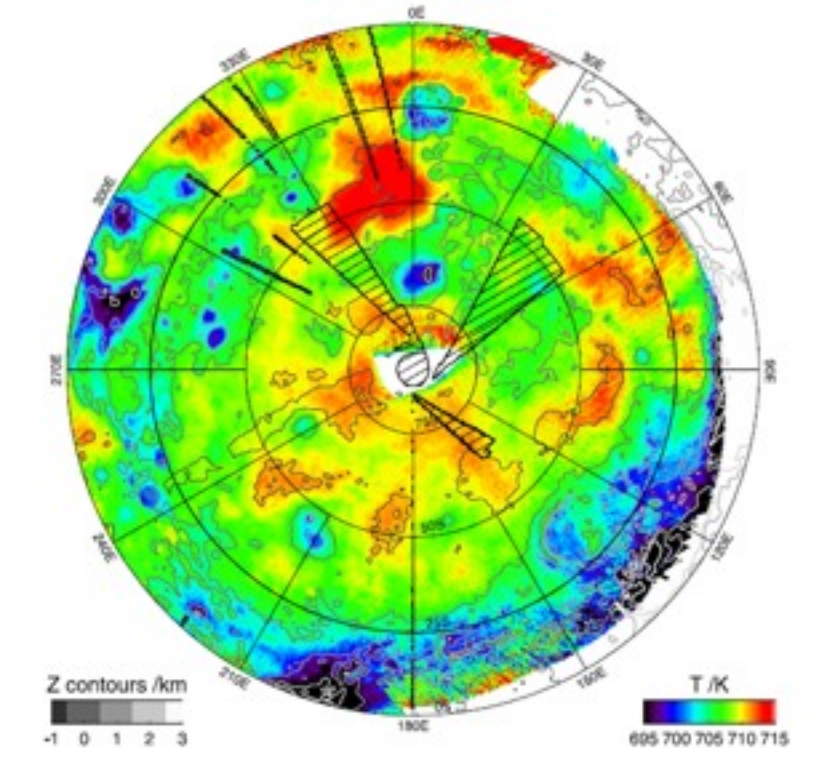
Venus' climate is an interconnected system of atmospheric, geologic, and surface chemistry processes, just like the Earth's.

Was Venus once habitable?

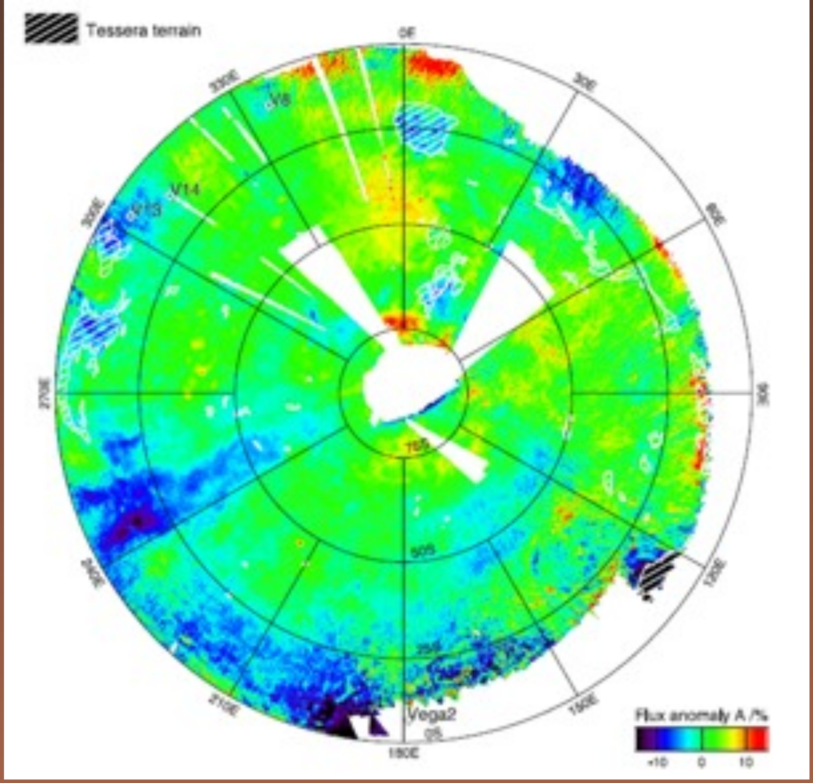
Is there continent-like crust on Venus?

Continental crust requires large amount of water in the mantle

Highlands (tessera) are brighter than plains



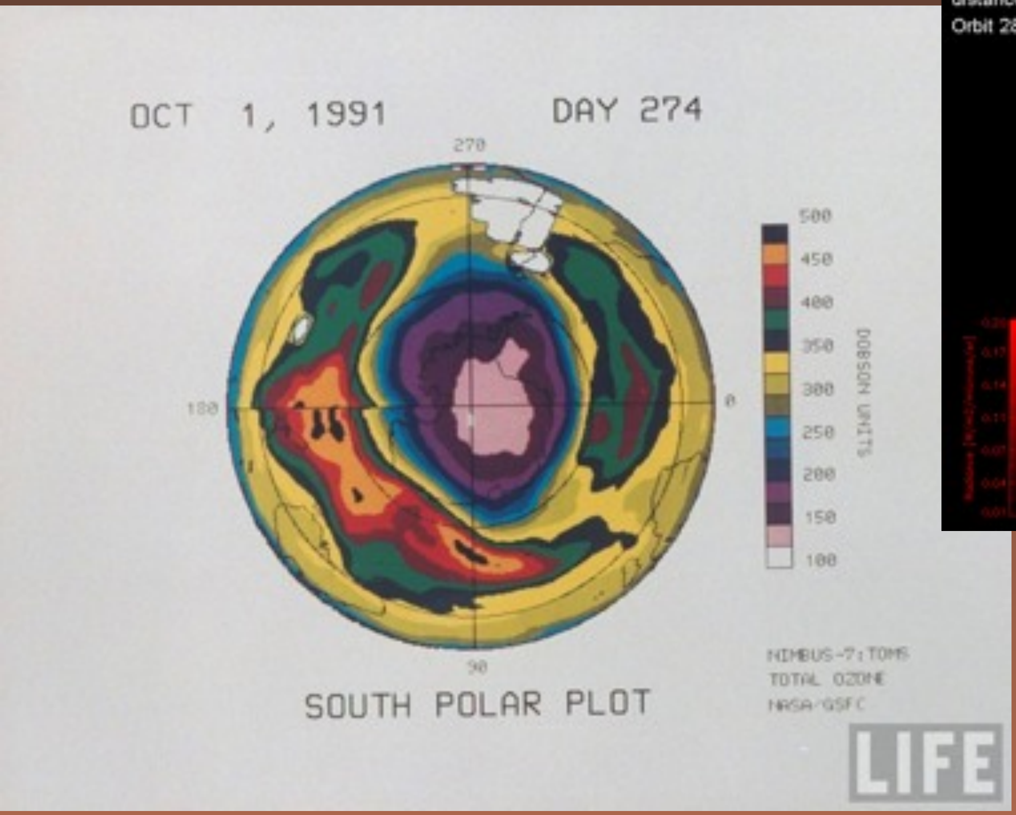
1 μm emission maps VIRTIS/VEX

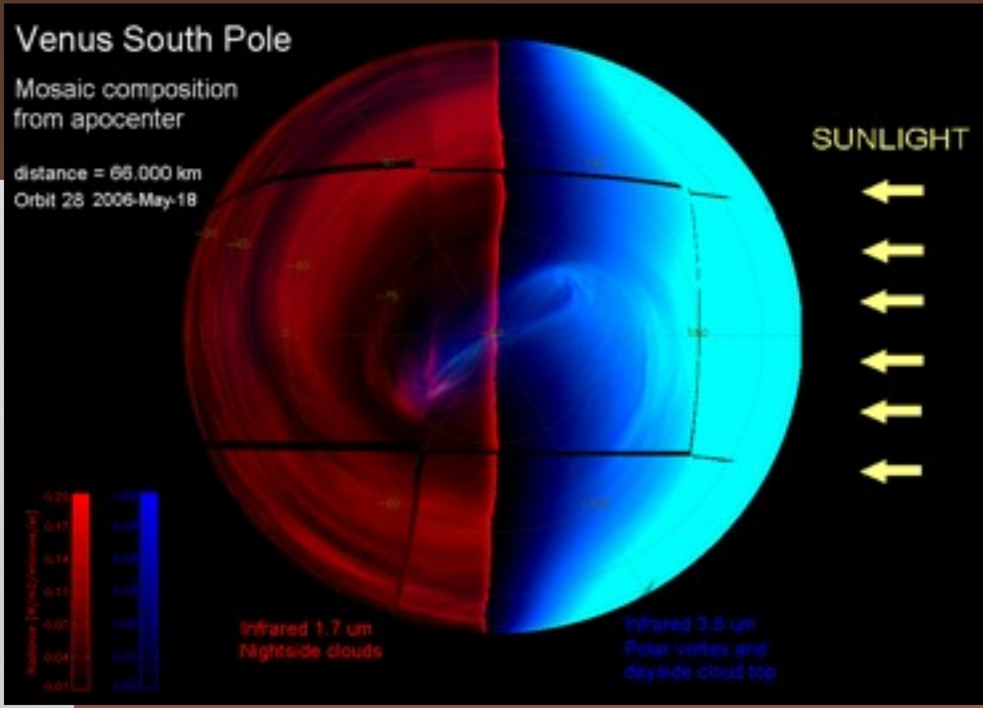


1 μm emission maps, temperature removed

Learning about Earth by Studying Venus

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



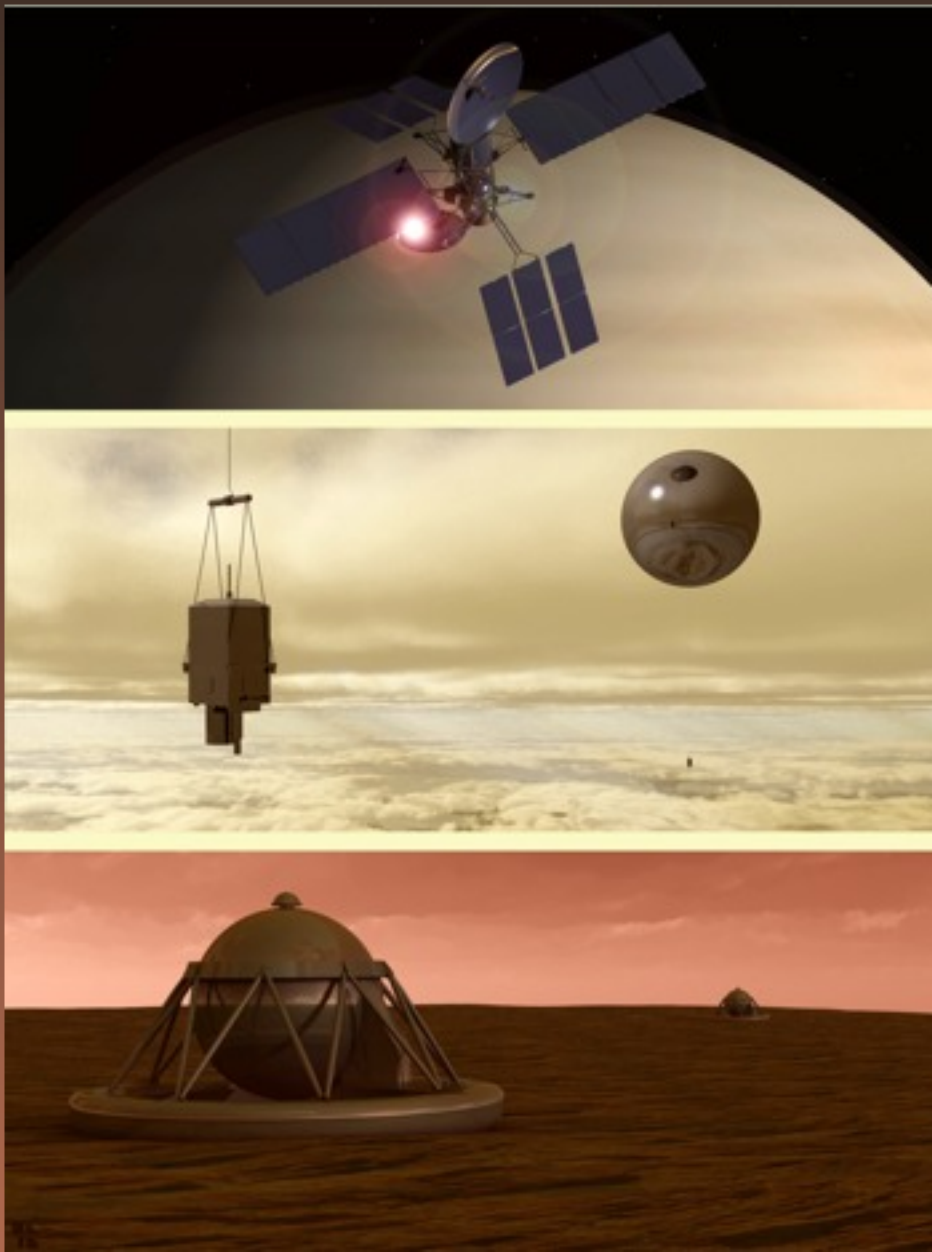


South polar vortex of Venus exhibits instability and ways to test Earth atmosphere dynamics VEX (left IR emission, right solar reflection)

Design Reference Mission Architecture for Detailed Study

Phase 2

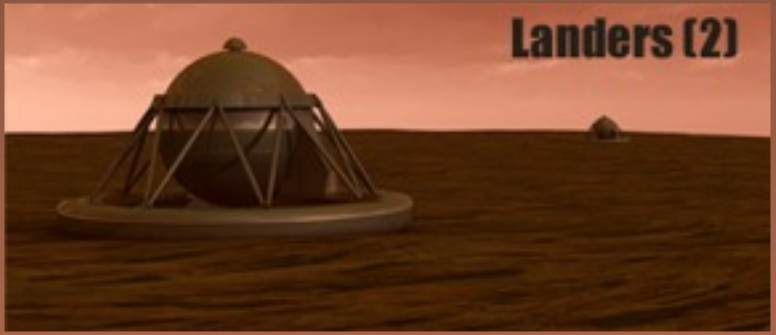
- A science-optimized **robust mission architecture** was identified, that
  - **Meets all the highest science priorities**
  - Has the **highest Figure of Merit** (FOM)
- A **capable long-lived orbiter** (years) with high resolution radar imaging and topography
- **2 instrumented balloons** between 52 and 70 km (1 month)
- **2 landers with extended surface life** (5 hours) that also acquire detailed atmospheric data on descent



The Design Reference Mission

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.



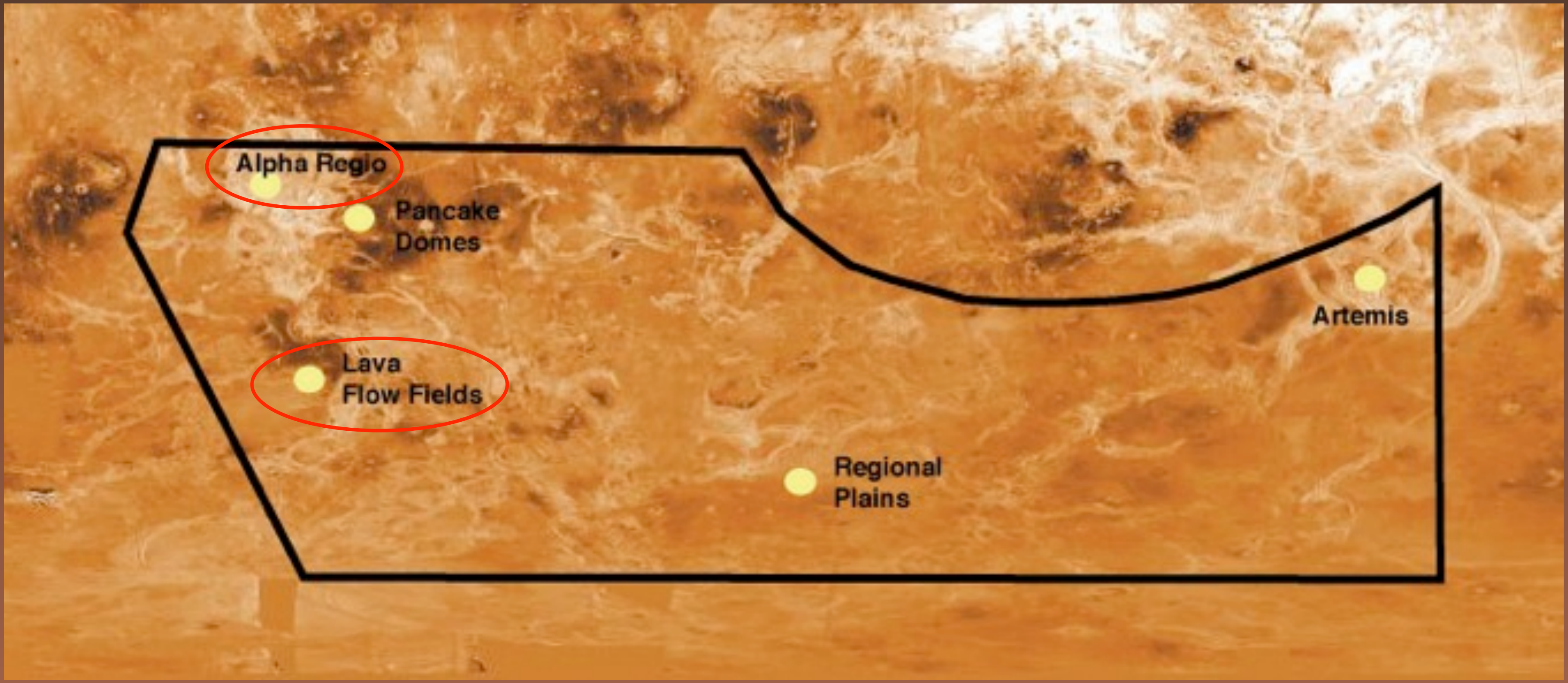
Venus DRM Planning Payload

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

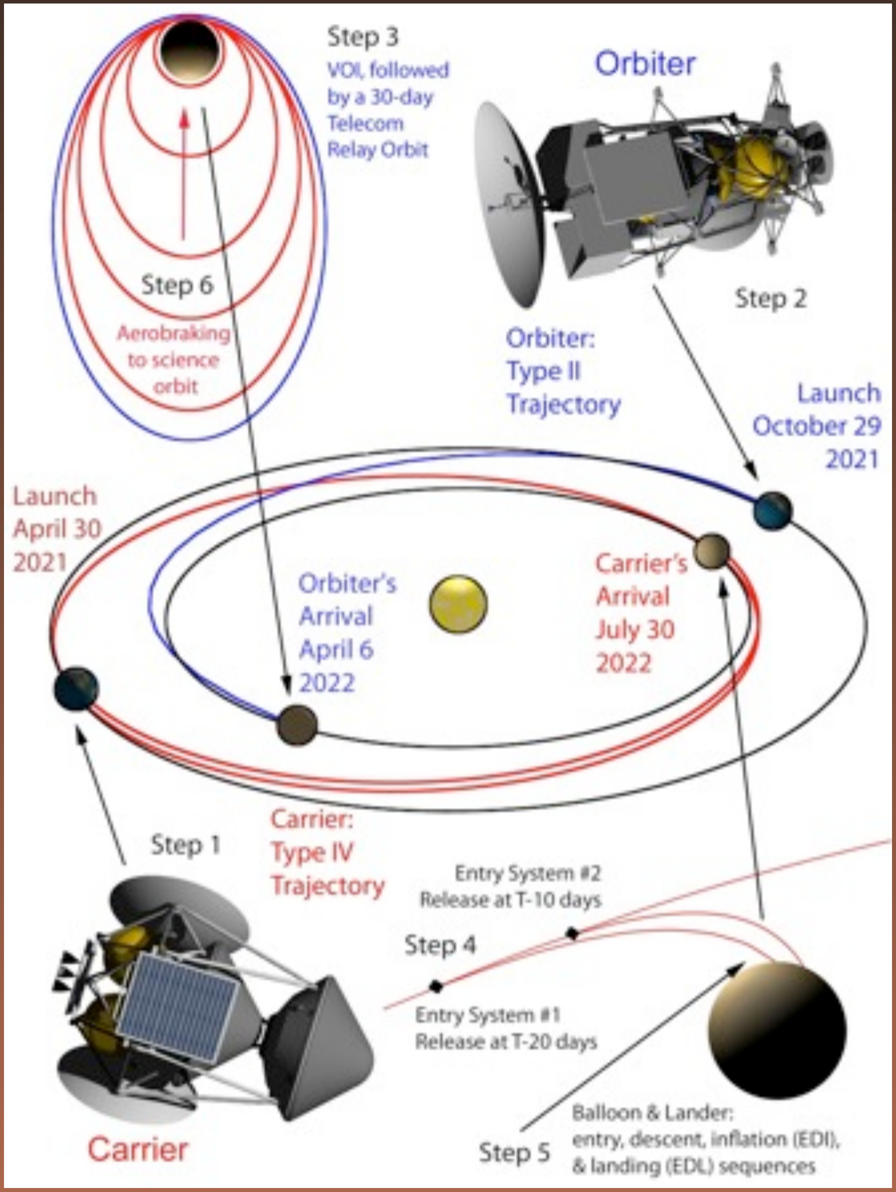
290.4 kg payload **22.5 kg (x2) payload** **106.2 kg (x2) payload**

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**.

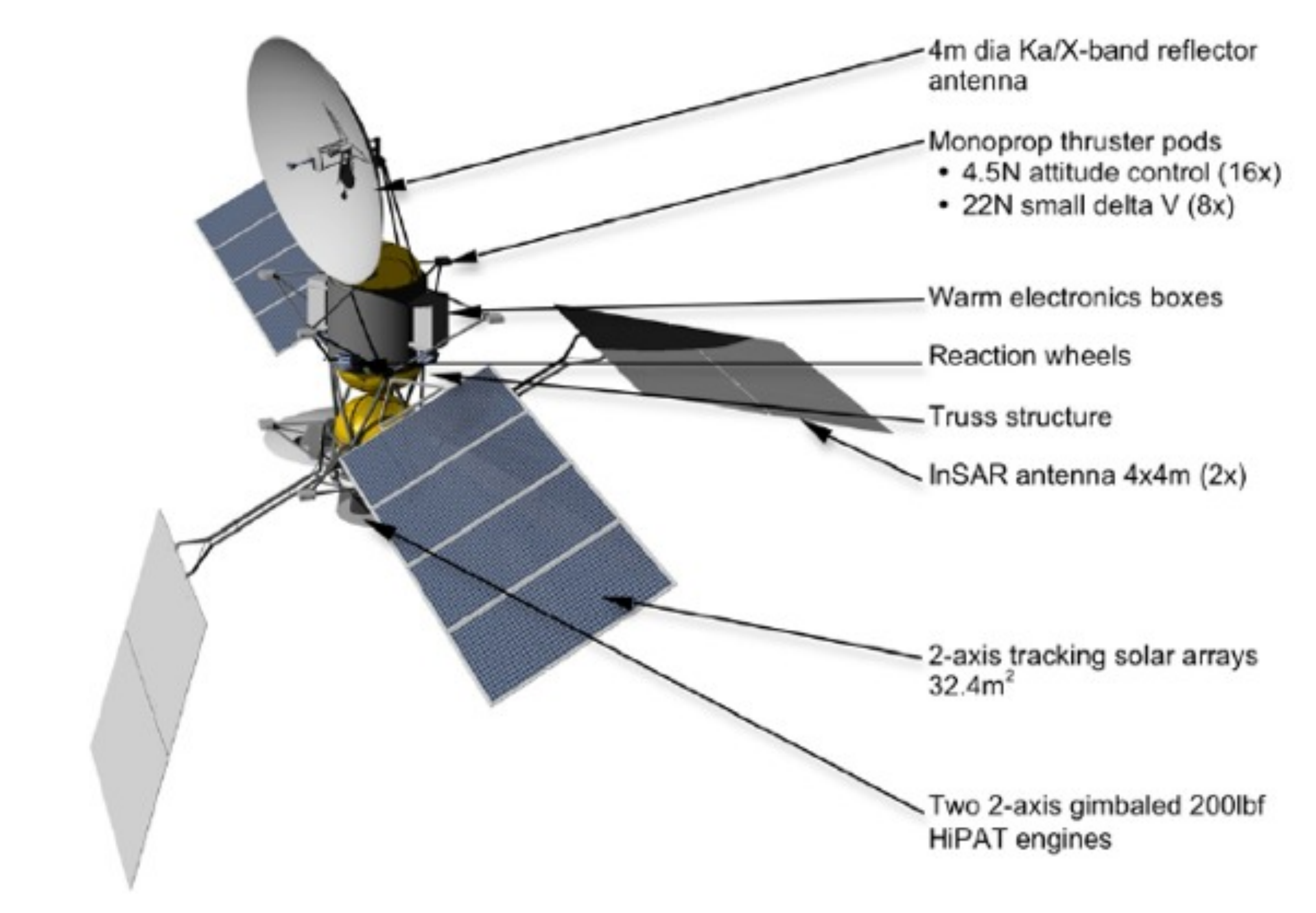


Mission Design



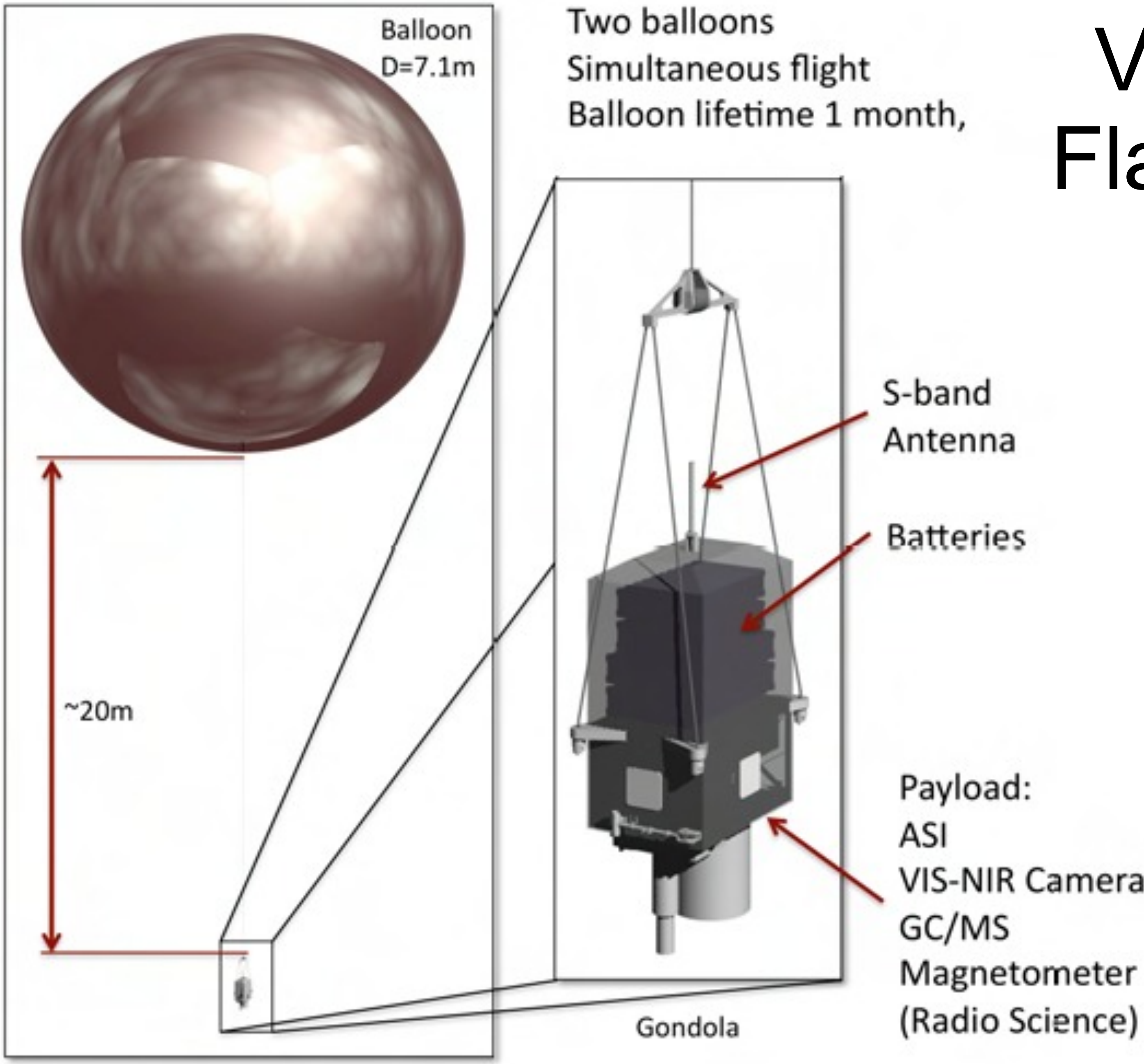
- Carrier with entry vehicles launches first, arrives second
- Orbiter launches second, arrives first and sets up to be a telecom relay in a 300 x 40000 km near polar orbit
- Entry vehicles arrive 13 hours apart so only 1 lander communicates with the orbiter at a time
- After 1 month of balloon mission,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

Orbiter

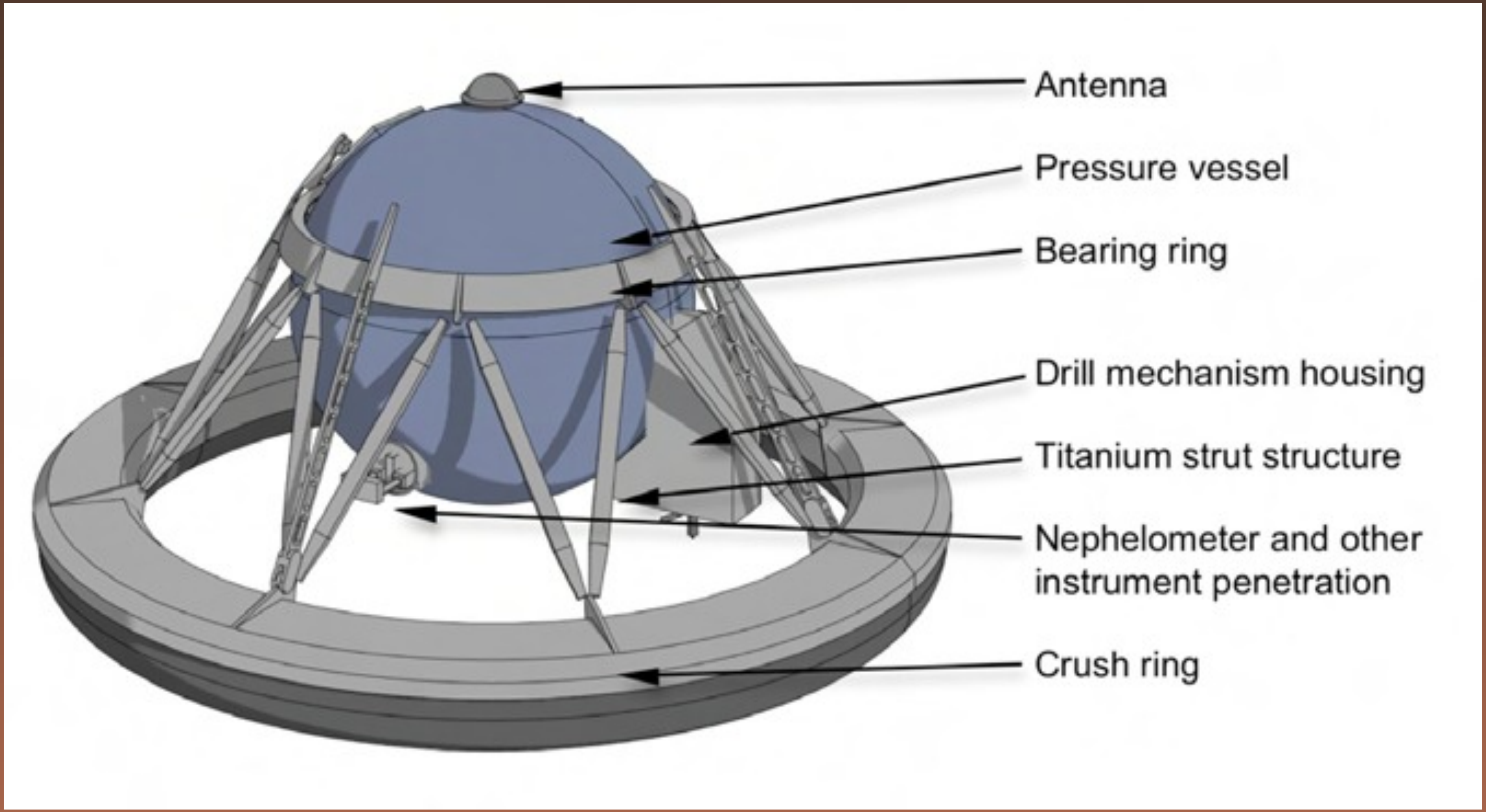


4m dia Ka/X-band reflector antenna
Monoprop thruster pods
• 4.5N attitude control (16x)
• 22N small delta V (8x)
Warm electronics boxes
Reaction wheels
Truss structure
InSAR antenna 4x4m (2x)
2-axis tracking solar arrays 32.4m²
Two 2-axis gimbaled 200lbf HiPAT engines

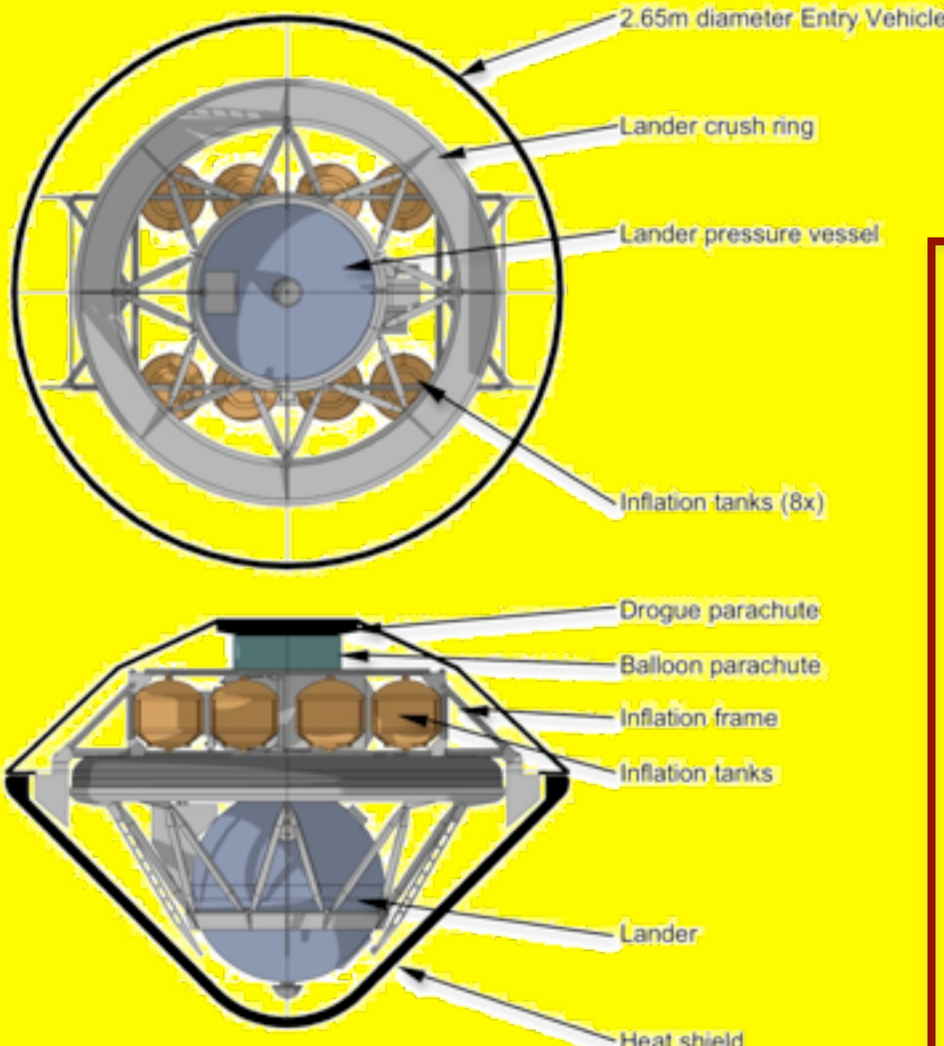
Venus Flagship



Venus Flagship Landers



DRM Carrier & Two Entry Vehicles



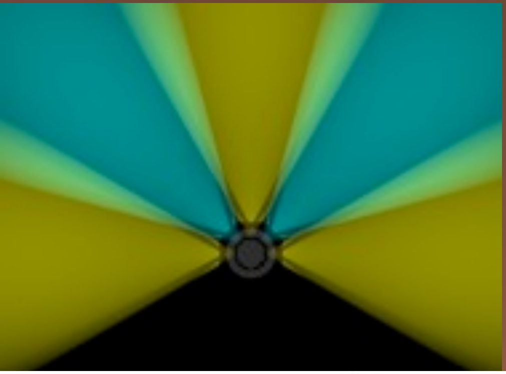
The two **entry vehicles** are Pioneer-Venus and Galileo style 45º sphere cone aeroshells, sized at 2.65 m diameter to accommodate all internal components.

Launch on Atlas V-551

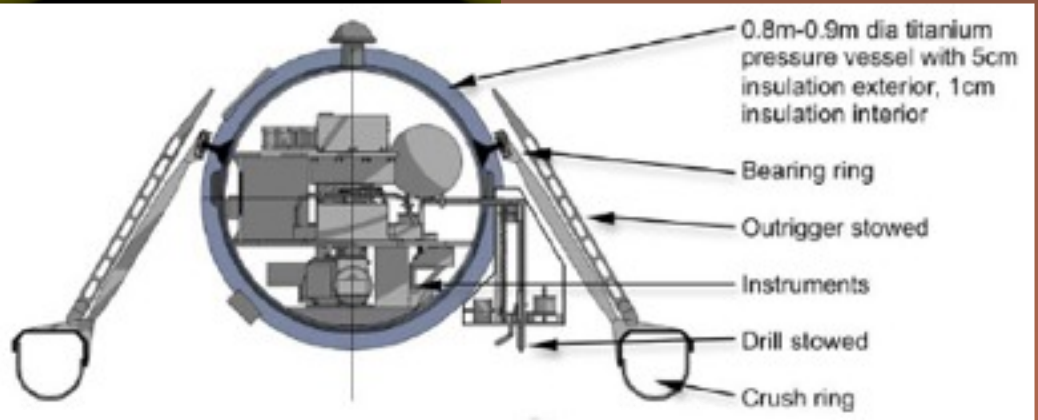
The **carrier** uses an stacked configuration (inline) for the entry vehicles. There is ample room inside the 4.5 m launch vehicle fairing.

Carrier = 1640 kg
Entry System = 1969 kg (x2)
Total (CBE+cont) **= 5578 kg**

Landers and Balloons



Artist's concept of Venus flagship lander on surface (pressure vessel can rotate for drill placement and image panoramas)
Lander mass = 686 kg (x2)

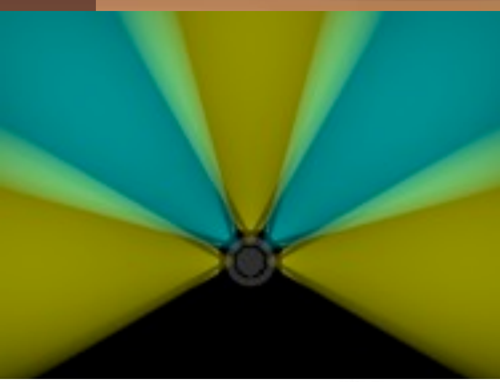


Artist's concept the Venus balloon (d=7.1m) in the super-rotating atmosphere

Balloon mass = 163 kg (x2)

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

Landers and Balloons



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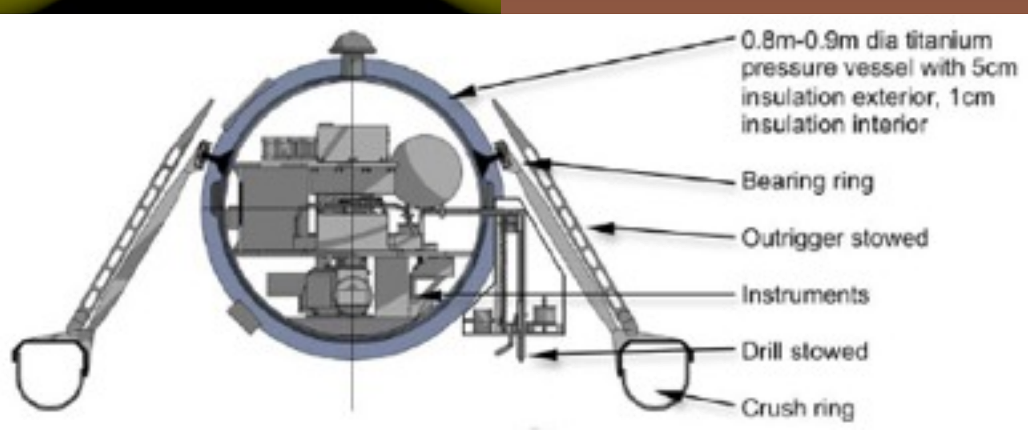
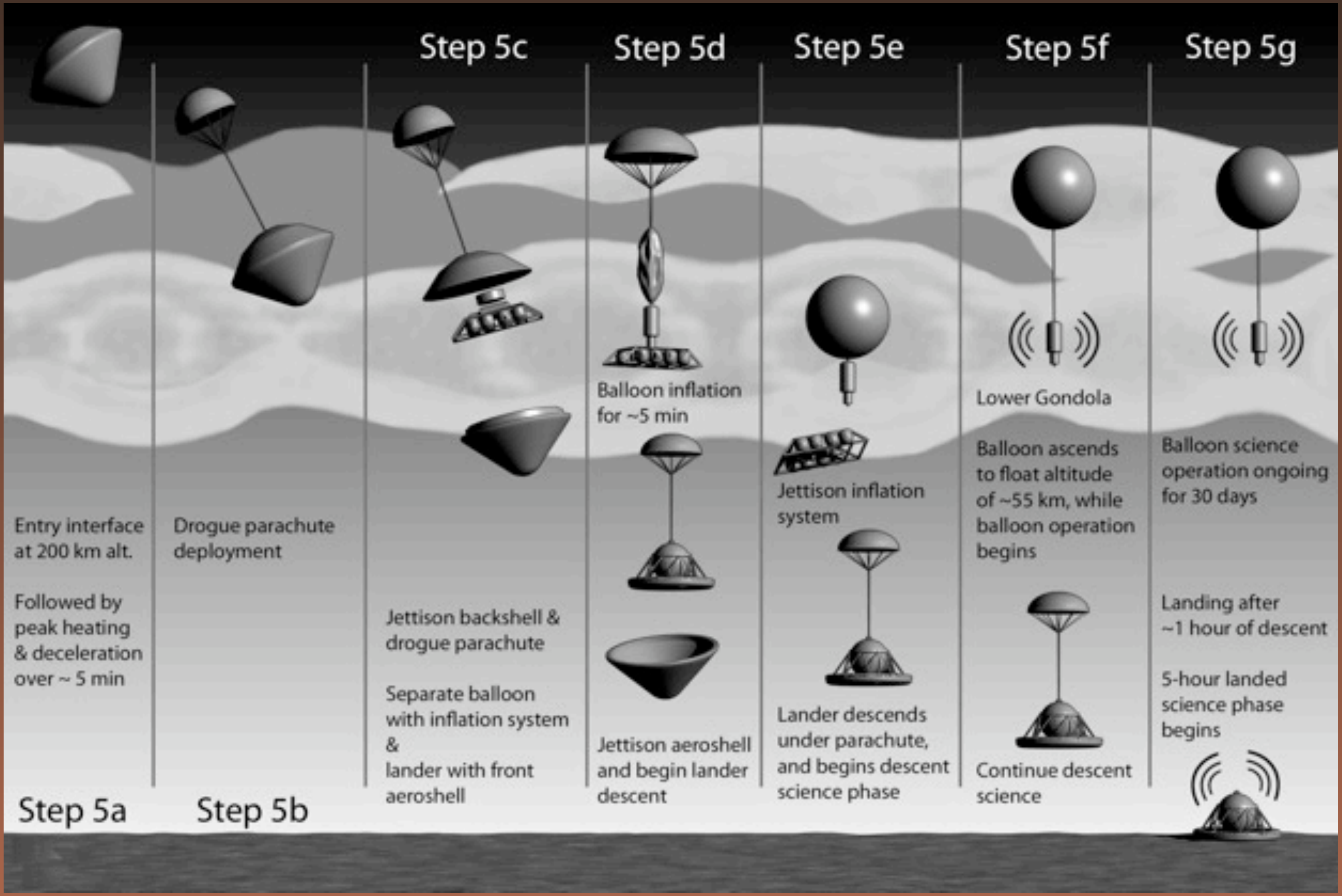


Artist's concept the Venus balloon (d=7.1m) in the super-rotating atmosphere

Balloon mass = 163 kg (x2)

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.

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.

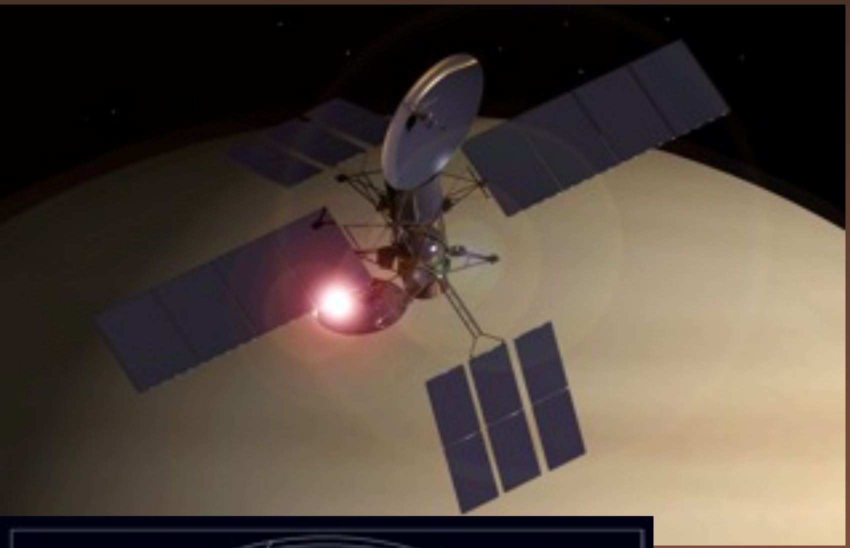
DRM Cost Estimates

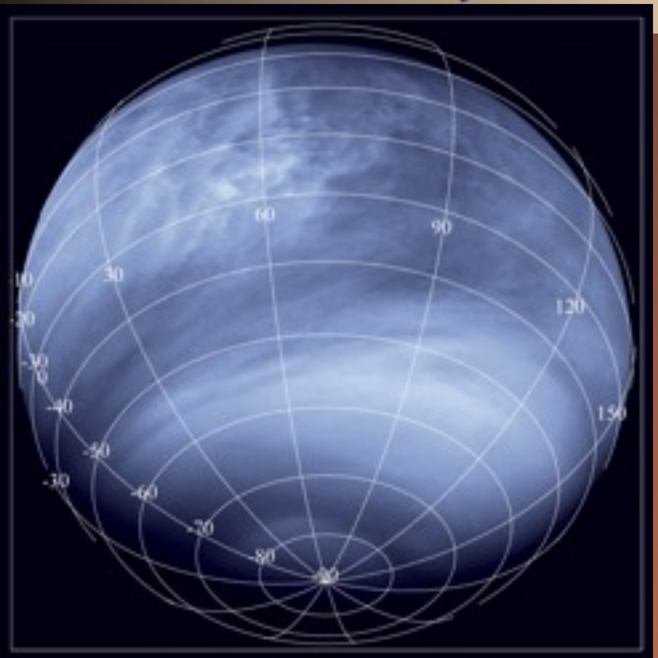
- The JPL cost-complexity model (Peterson et al, 2008) gave a $2.7B estimate for the Design Reference Mission
  - The stated accuracy of this model ~40% on absolute cost, implying a maximum possible cost of $3.8B.
- The JPL study team created a second cost estimate that fused three sources: JPL's Team 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

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

Technology Challenges

Outline

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

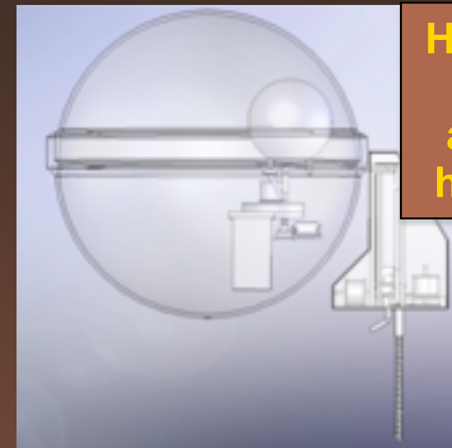
- Technologies for enhancements to DRM architecture and design

- Technologies for Surface Science Enhancements - new mission architectures

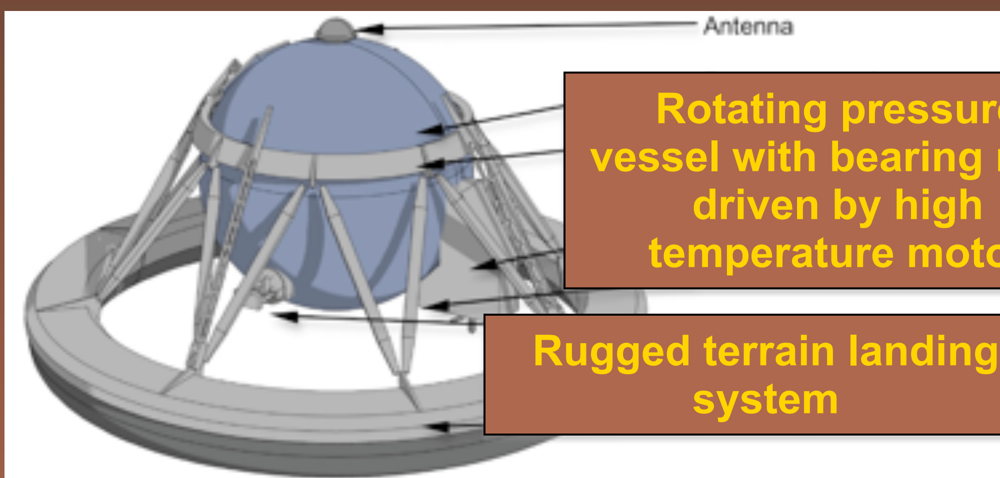
- Technology development priorities

Technology Development for DRM

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



High temperature sample acquisition and handling system



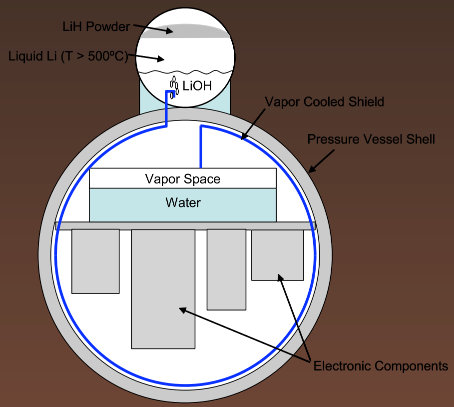
Rotating pressure vessel with bearing ring, driven by high temperature motor

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

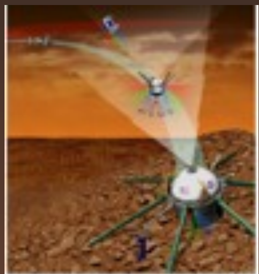
Advanced passive thermal control options:

- 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

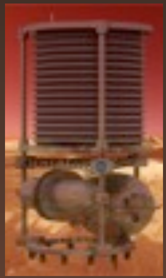
Surface Science Enhancements



Seismometer and Meteorological Network

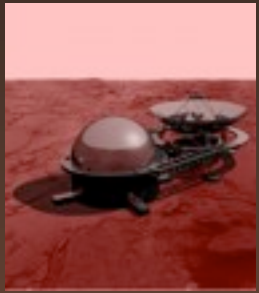
- Require long-lifetime measurements on the surface to
- Provide measurements of the size-frequency distribution of seismic events
- Surface meteorology with measurements such as temperature, wind speed and direction, and pressure
- Provide correlation between observed planetary events and changes in

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

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.