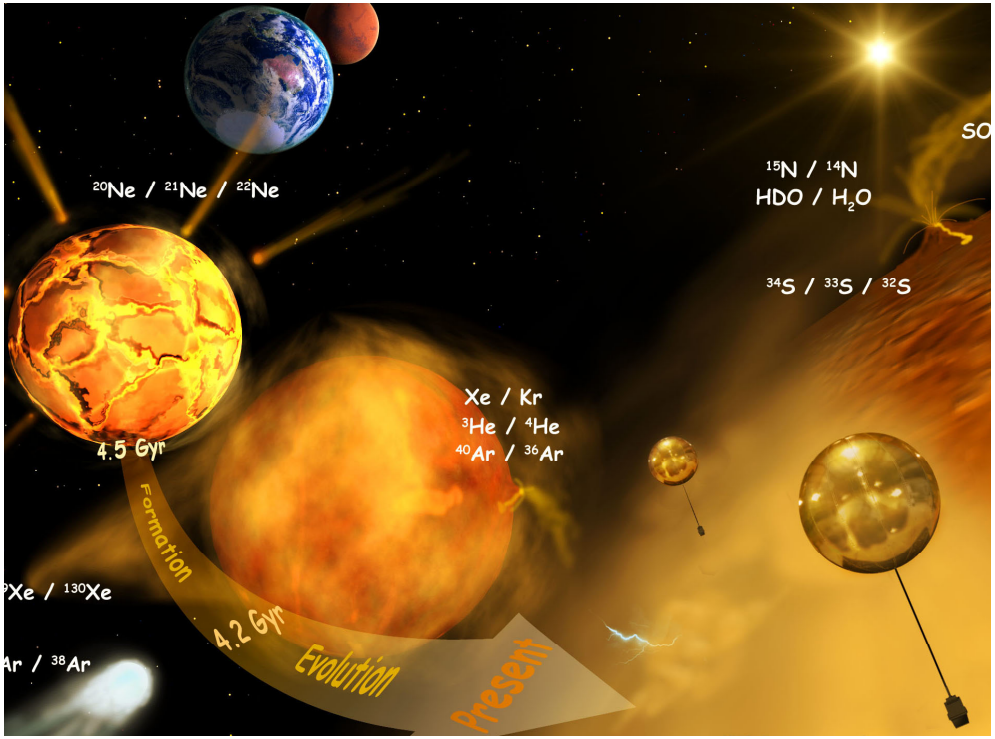
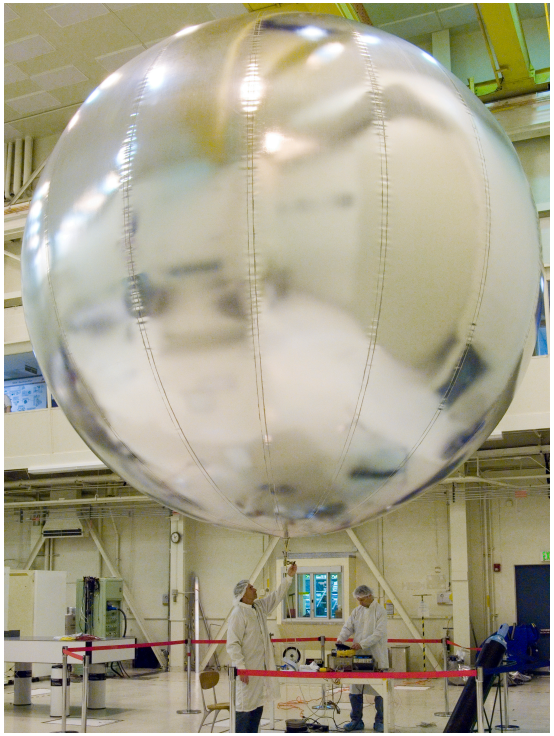
EXPLORING VENUS WITH BALLOONS: SCIENCE OBJECTIVES AND MISSION ARCHITECTURES

K. H. Baines, S. K. Atreya, A. Chutjian, D, Crisp, D. L. Jones, J. L. Hall,
V. V. Kerzhanovich, S. S. Limaye, C. T. Russell, S. Stephens, and K. Zahnle





5TH International Planetary Probe Workhop
Bordeaux, France, June 25-29, 2007

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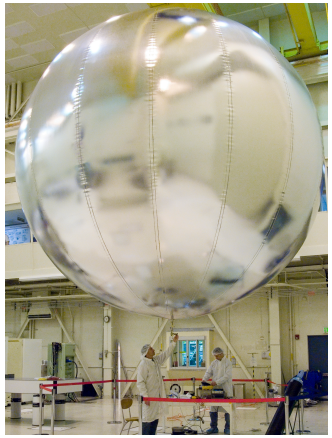


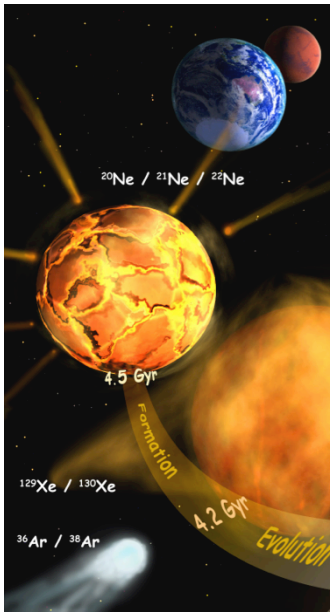
Outline

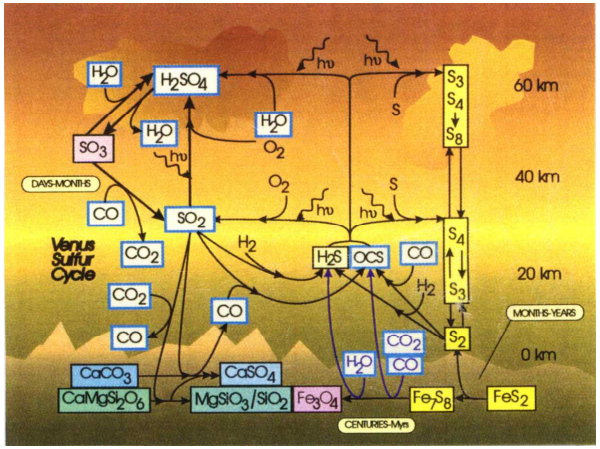
-Why Explore Venus?

-Venus Exploration Today

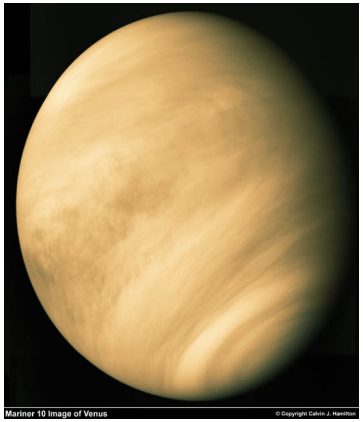
- Science Objectives for Middle-Atmosphere Balloons

-Status of Case Study: VALOR Discovery Mission



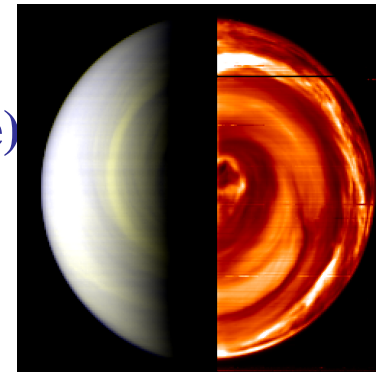


Why Explore Venus?



Earth's Twin Sister Planet…..

- Common size, in both volume and mass
- Common bulk composition and gravity
- Common position from the Sun
- Common effective temperature at cloud level, with common pressure/temperature structure there

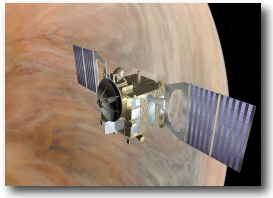


…Gone awry….

- Dry (~ 30 ppm vs ~300,000 ppm for Earth's atmosphere)
- Sulfuric acid clouds, not water
- 740 K (470 C) at surface, not Earth-like pre-Mariner predicted ~300 K, as on Earth
- Slow, retrograde spin (118 Earth days is a solar day)
- Yet - Hurricane-force winds virtually everywhere, from the ground to over 120 km altitude

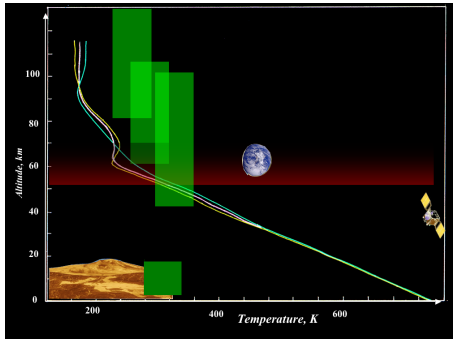
Alien Structure, Chemistry, Dynamics, and Geology Today,
Due to both Cataclysmic and Subtle Events in the Past,
With Key Lessons for Earth's Future.

VENUS EXPLORATION TODAY

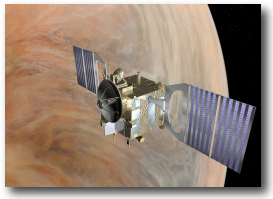


On-Going Orbital Reconnaissance by ESA's Venus Express

- Since April 2006
- Studies of Sun/Venus interactions, global atmospheric dynamics, cloud chemistry and physics, surface properties
- Approximately 150 Gbits of data returned
- Images, spectra, movies, stellar occultations, plasma and magnetometer measurements



VENUS EXPLORATION TODAY



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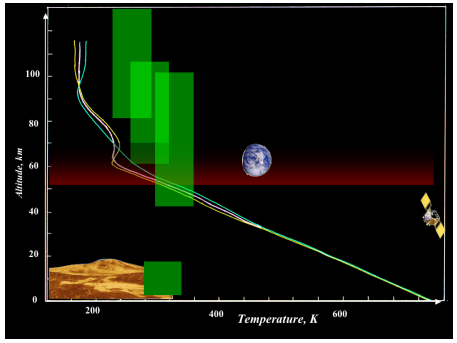
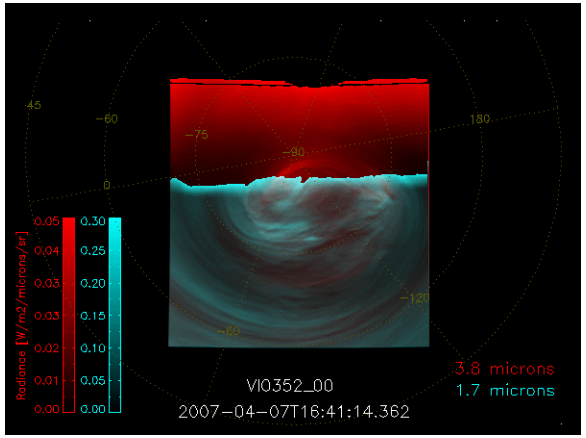
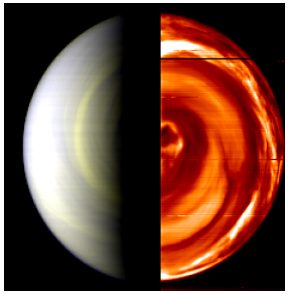
- Since April 2006
- Studies of Sun/Venus interactions, global atmospheric dynamics, cloud chemistry and physics, surface properties
- Approximately 150 Gbits of data returned
- Images, spectra, movies, stellar occultations, plasma and magnetometer measurements
- Highlights thus far:
  - South Polar Dipole 3-D studies
  - Lightning Detection (with MAG)
  - Bistatic RADAR studies
  - Trace chemicals in upper atmosphere via occultations
  - Ground mapping.
    - Volcano search and Emissivity mapping ongoing



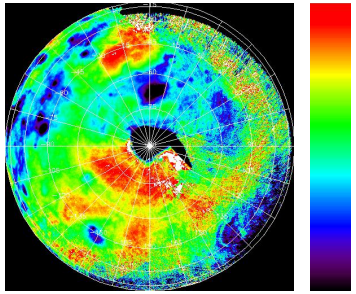


Polar Diple Movie:
1.7-um Nightime emission (50-km cld clearings)
3.8 -um emission (65-km temp emissions, both clouds and gas)



Day
Upper-cloud reflectivity

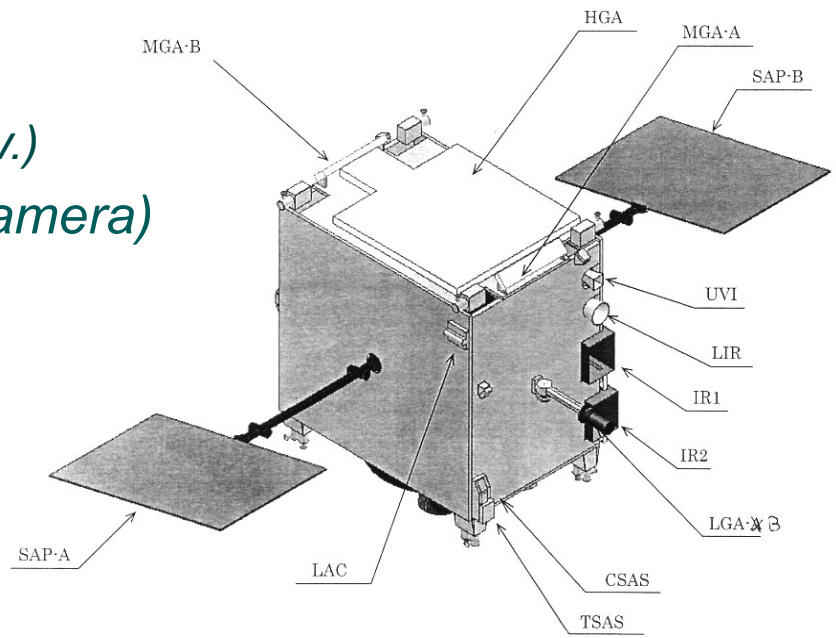
Night
Deep-Cloud Transparency



Surface Temps/Elevation Southern Hemisphere

Planned Reconnaissance By Japan's Venus Climate Orbiter (VCO)

- Launch in 2011, Arrival in 2012
- Multiple cameras for imaging global dynamics and surface
- Radio Science with USO

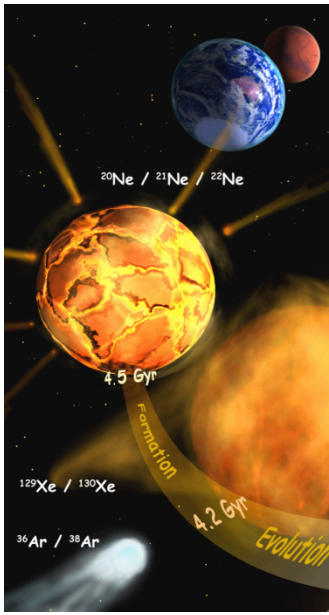


- ***UVI*** *(Ultraviolet Imager)*
  Shigeto Watanabe (Hokkaido Univ.)
- ***LAC*** *(Lightning and Airglow Camera)*
  Yukihiro Takahashi (Tohoku Univ.)
- ***IR1*** *(1-μm Infrared Camera)*
  Naomoto Iwagami (Tokyo Univ.)
- ***IR2*** *(2-μm Infrared Camera)*
  Takehiko Satoh (ISAS/JAXA)
- ***LIR*** *(Long-wave IR Camera)*
  Makoto Taguchi (Nat'l Institute for Polar Res.)
- ***USO*** *(Ultra-Stable Oscillator)*
  Takeshi Imamura (ISAS/JAXA)

The Next Step: *In-Situ* Exploration
Experiencing Venus

Salient Science Measurements Unachievable From Orbit

- Noble Gases and Their Isotopes
- Isotopes of Light Gases



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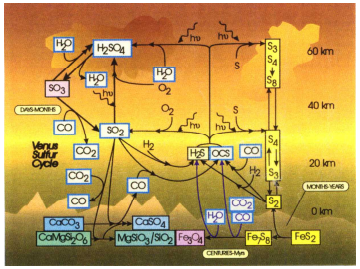

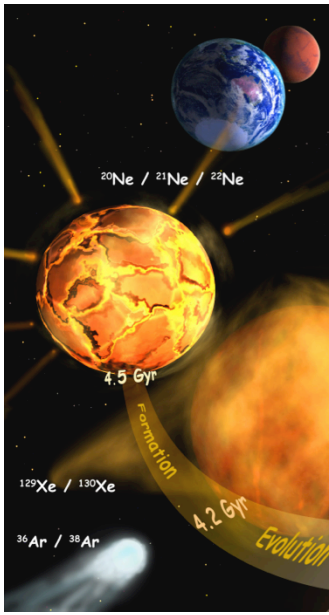

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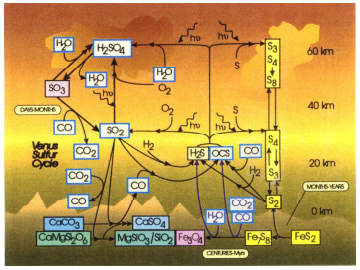
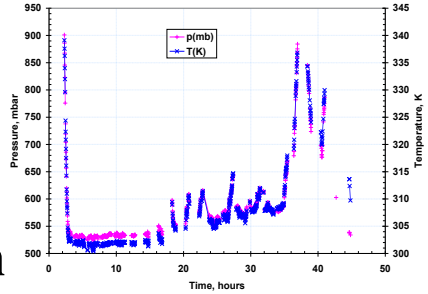
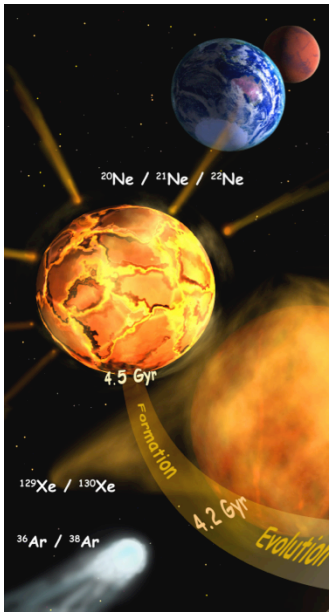
- Vertical Character of Dynamics
  - Gravity Waves
  - Convection
  - Hadley Cell
- Meridional Character of 3-D Circulation







The Next Step: *In-Situ* Exploration Experiencing Venus

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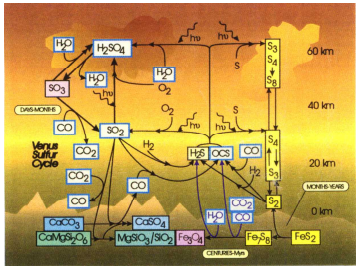
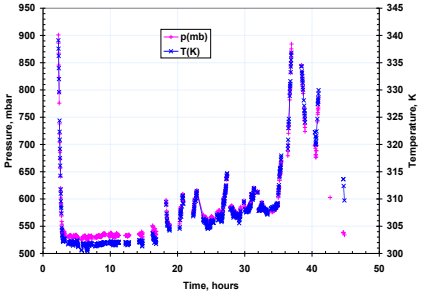
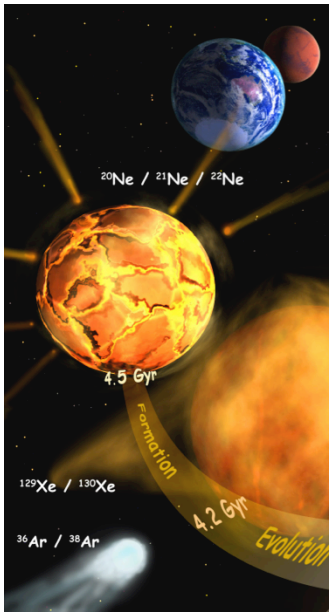
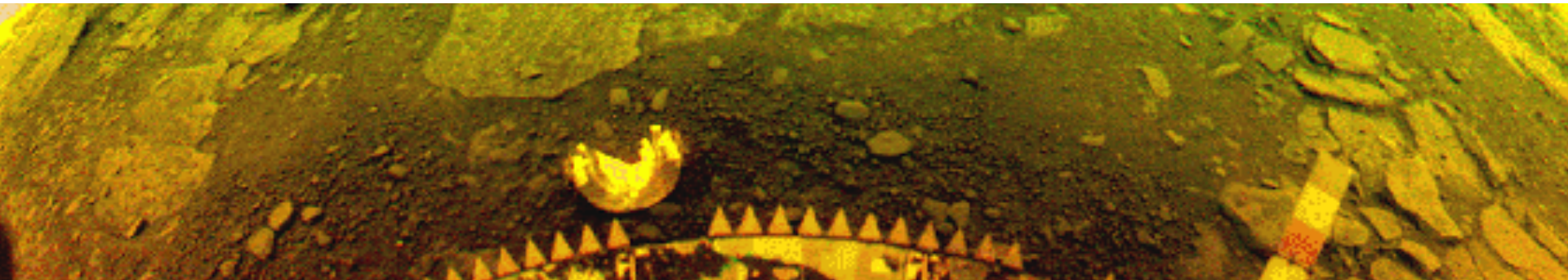
- Meridional Character of 3-D Circulation
- Surface Composition, Mineralogy, Age
- Seismic Measurements









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Experiencing Venus

Salient Science Measurements Achievable with Mid-Altitude Balloon

- Noble Gases and Their Isotopes
- Isotopes of Light Gases
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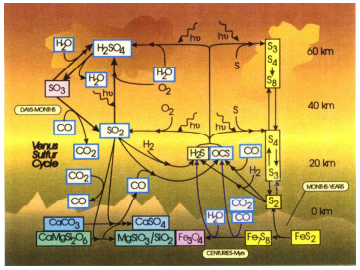

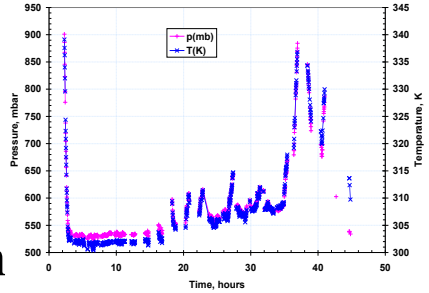

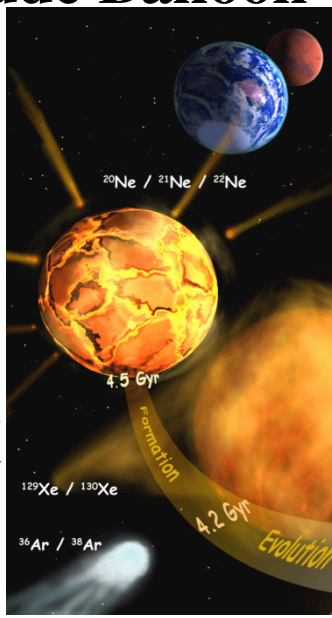

VEXAG Draft
Salient Science Objectives
Vs Mission Class

Table IV-1. Traceability Matrix of Objectives Met with Discovery, New Frontiers, and Flagship Missions.

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

Convention: ● *Major Contribution* ▲ *Supporting Contributions*

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

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Salient Science Objectives Vs Mission Class

High-Altitude Balloons Address and Satisfy Numerous High-Priority Science Issues

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Example Missions:

European Venus Explorer (EVE) Cosmic Vision Mission

Venus Aerostatic-Lift Observatories for in-situ Research

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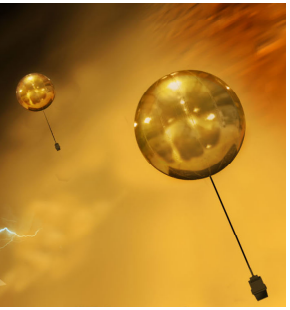
Case Study: VALOR Discovery Mission

VALOR: Venus Aerostatic-Lift Observatories for *in-situ* Research



***In-situ*, Long-Duration, Wide-Ranging Exploration of our Sister World**

- **By Successfully Flying the Skies of Venus**
- **On a Multi-day Mission Spanning a Large Range of Longitudes/Latitudes**
- **Including Plans for Circumnavigation of the Globe**

Case Study: VALOR Discovery Mission
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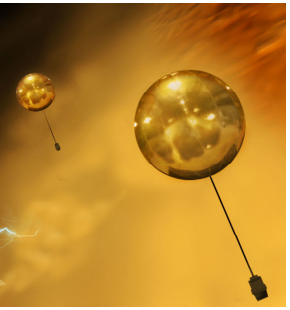

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Validation of Entry/Descent/(EDI) and Balloon Operations for the Exploration of Distant Planets (e.g., Titan)

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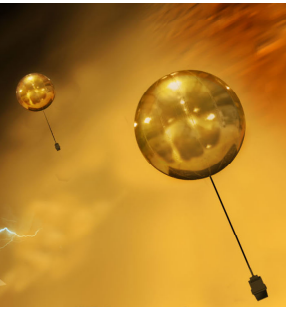

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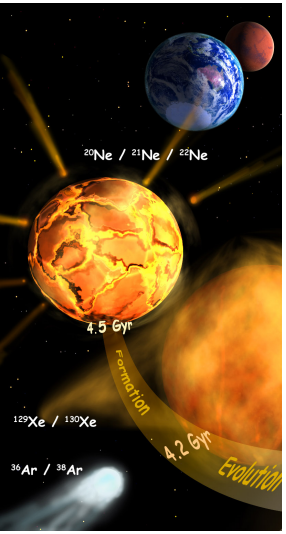
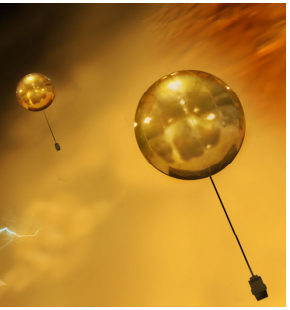


Prime Science Objectives:

- **Determine Isotopic Ratios of Heavy Noble Gases,**
  Key to Understanding the Origin and Evolution of Venus

Case Study: VALOR Discovery Mission
VALOR: Venus Aerostatic-Lift Observatories for *in-situ* Research



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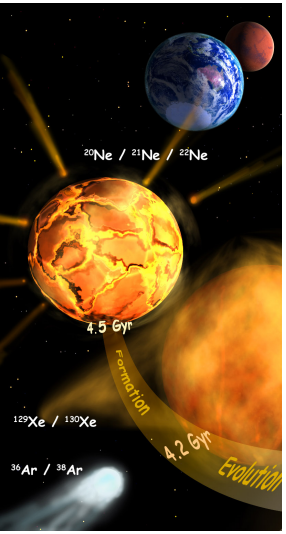

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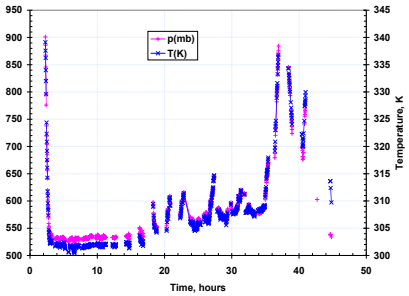
  - **Extent of Hadley Cell Structure**
  - **Physics of Global Super-Rotation**



Case Study: VALOR Discovery Mission
VALOR: Venus Aerostatic-Lift Observatories for *in-situ* Research

***In-situ*, Long-Duration, Wide-Ranging Exploration of our Sister World**

- **By Successfully Flying the Skies of Venus**
- **On a Multi-day Mission Spanning a Large Range of Longitudes/Latitudes**
- **Including Plans for Circumnavigation of the Globe**

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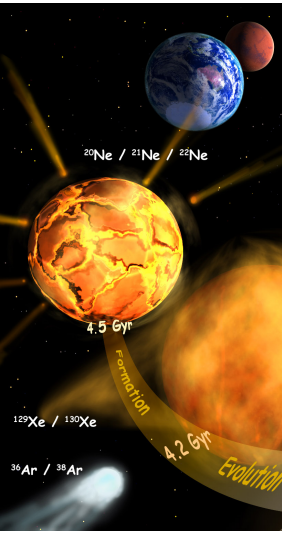

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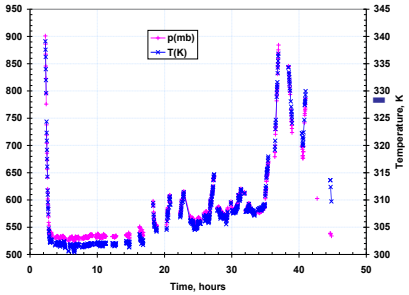
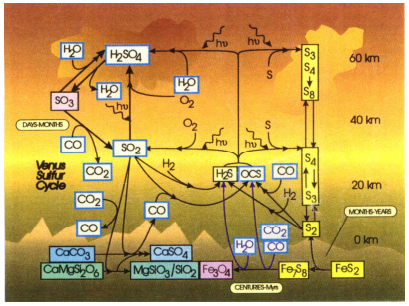
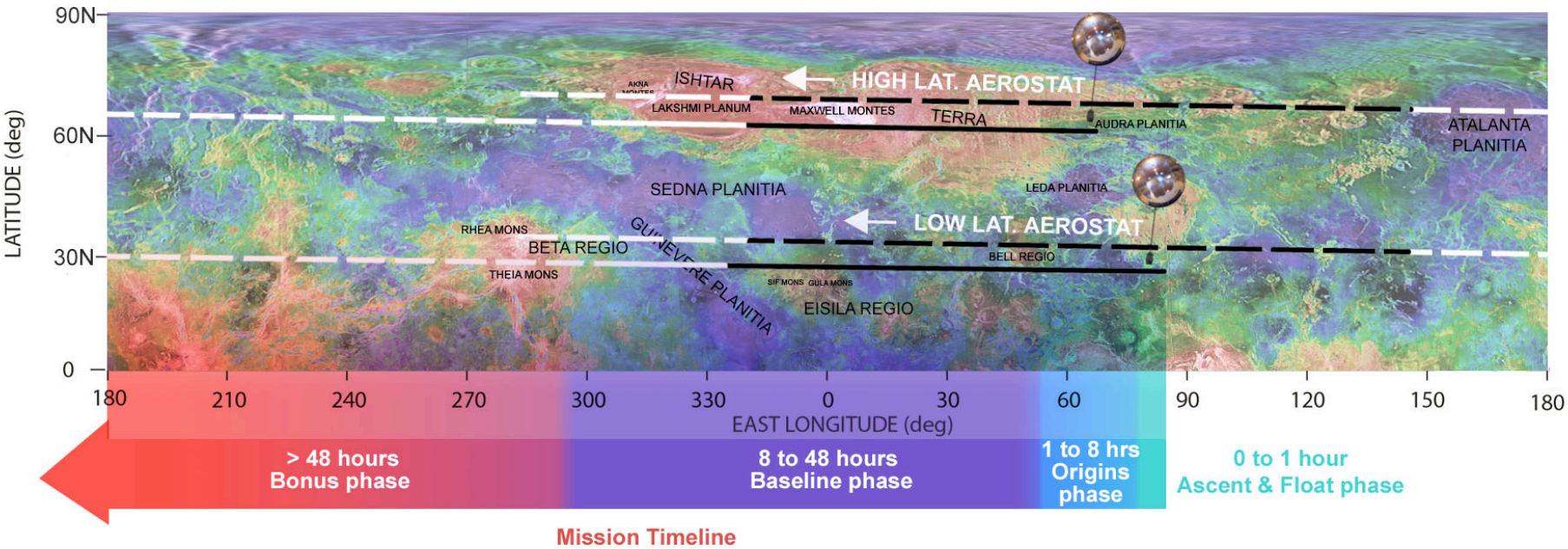


Investigate Sulfur-Based Meteorology

- **H_2SO_4 aerosols and their parent gases**
- **Convection and Lightning**
- **Diurnal, Vertical, NS Latitudinal Sampling**



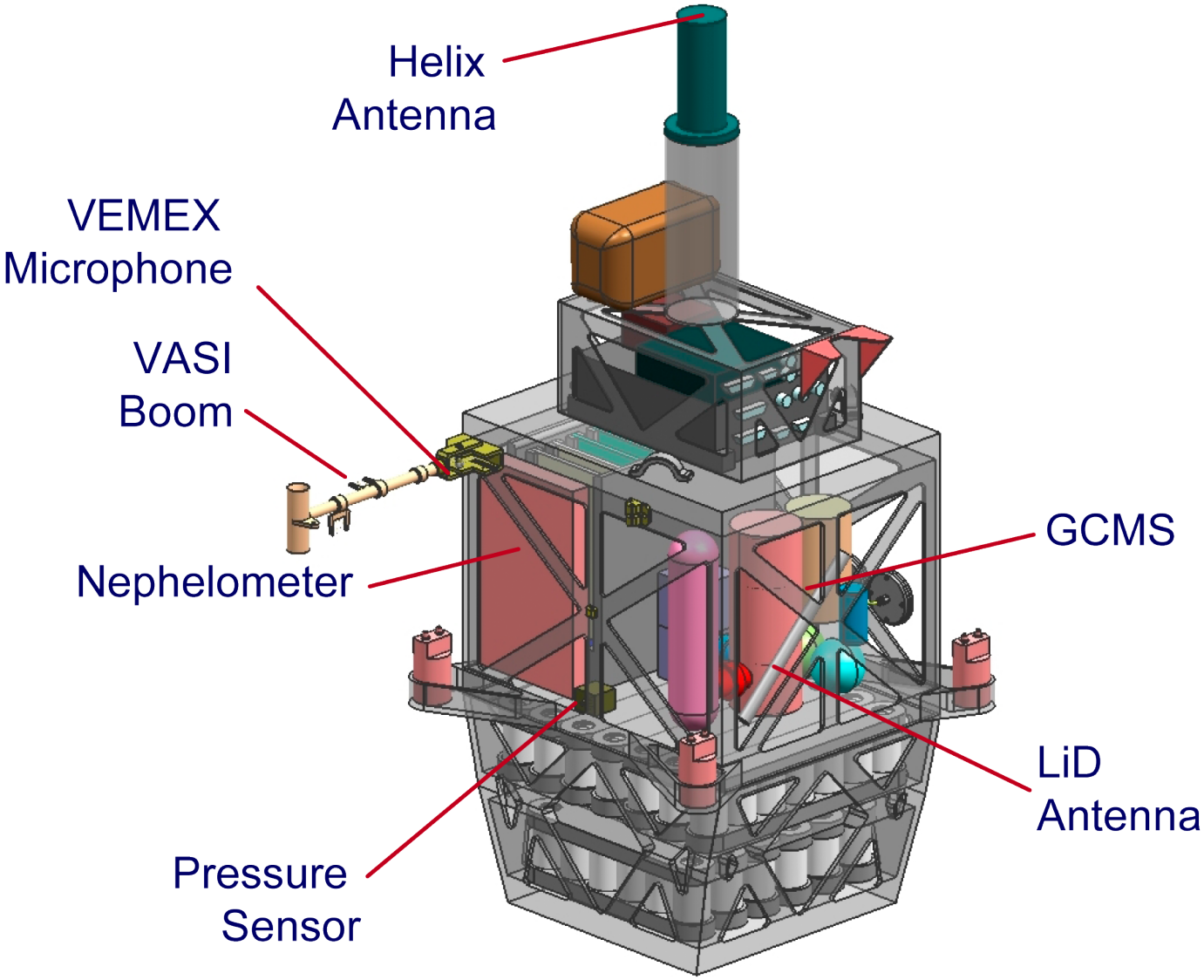
VALOR Flight Paths
Dual Balloons Circumnavigate Venus
During Planned 8-Day Mission



Mean Float Altitude: 55.5 km
Mean Ambient Pressure: 500 mbars
Mean Ambient Temperature: 24 C

Begin on Nightside, East limb (relative to Earth)
Drift westward at ~ 300 km/hr (180 knots)

VALOR Instrument Complement

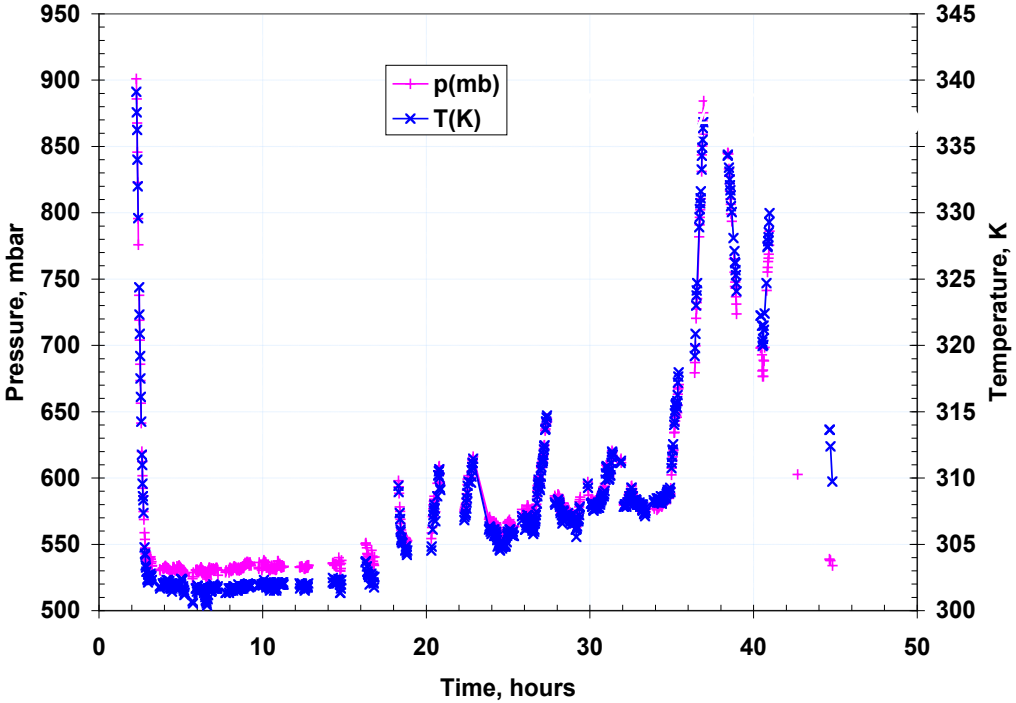


Riding the Waves of Venus

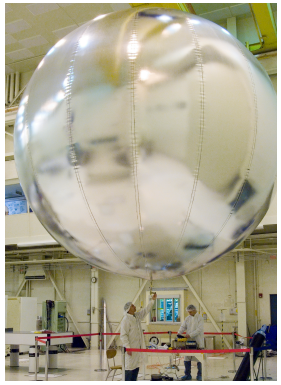
VEGA regularly "bobbed" vertically ~ 3 km riding gravity waves

VALOR will "bob" ~ 1 km

- **Will measure, directly, 3-D winds at high temporal and spatial resolution**
- **Will measure vertical motion and wave characteristic**
- **Will obtain direct measurements of zonal and meridional winds**
- **Uses radio tracking, pressure, and temperature sensors together with aerobot aerodynamic modelling for precise measurements of 3-D winds**



VALOR: Building on VEGA



Characteristics	VEGA	VALOR	VALOR Enabling Science
Latitudes explored	7°N and 7°S	25°N and 60°N	Flights within two distinct latitude regions enable characterization of Hadley cells, diverse waves (Ishtar Terra overflight)
Data volume for two aerostats (Mbits)	0.2	>18	Dynamics statistics, environmental variabilities, low wave detection threshold, detailed structure of convective cells
Max data rate (bps)	4	180	Fast sampling: convection/wave variability, synergistic science
Instruments/Measurements*			
Noble, light gas isotopic ratios (MSR*, accuracy)	N/A	7-13 min, 5%	Origin/formation/evolution of Venus; not addressed by VEGA
Chemically-active species abundances (MSR*, accuracy)	N/A	7 min, 5%	Cloud formation/evolution, meridional dynamics from tracers; not addressed by VEGA
Pressure (MSR*, accuracy)	75 s, 1 mbar	6 s, 1 mbar	High-res meteorology/dynamics: e.g., convection vs. waves
Temperature (MSR*, accuracy)	75 s, 0.5°C	6 s, 0.1°C	High-res meteorology/dynamics: e.g., convection vs. waves
Vertical wind (MSR*, accuracy)	75 s, 0.1 m/s	6 s, 0.1 m/s	High-res meteorology/dynamics: e.g., convection vs. waves
Doppler wind (MSR*, accuracy)	1 s, 0.5 m/s	1 s, 0.1 m/s	Global circulation, convection/waves, meteorology
Radio-tracked position (MSR*, accuracy, each measurement)	5 min, 15 km	30 s, 0.2 km	Global circulation, high-res meteorology/dynamics: e.g., convection vs. waves
Radio-tracked mean wind velocity (MSR*, accuracy)	1 hr, 6 m/s	1 hr, 0.1 m/s	Global circulation, convection/waves, meteorology
Cloud particles (MSR*)	75 s	6 s	Anatomy/evolution of clouds, meteorological phenomena
Mean particle radius (accuracy)	N/A	30%	Cloud particle variations: cloud evolution; unmeasured by VEGA
Local particle backscatter cross-section (accuracy)	5%	5%	Cloud particle variations: cloud evolution
Lightning detection (range)	N/A	500-km radius	Lightning emissions, NOx chemistry constraints; not on VEGA
Thunder detection (range)	N/A	5-km radius	Lightning power characterization; unmeasured by VEGA

* *MSR = maximum sampling rate.*

Noble and Light Gases: Science Objectives Current and Future Measurements

Constituent	Primary Science Objective	Current Measurements	Implied Uncertainty	Mission	Reference	Expected VALOR Uncertainty
Noble Gases						
^{132}Xe	Origin/evolution of terrestrial planets: Roles of blowoffs, comets, and planetesimals	~1.9 ppb	>200%		Donahue, 1986; Pepin, 1991	5%
^{84}Kr	Origin/evolution: Cold comets as atmospheric gas supplier	0.7 ± 0.35 ppm or 0.05 ± 0.025 ppm	>100% (average)	Venera Pioneer Venus	von Zahn et al., 1983 von Zahn et al., 1983	5%
^{36}Ar	Planetary origin: Roles of comets and planetesimals	31 ± 9 ppm	33%		von Zahn et al., 1983	5%
^{20}Ne	Planetary origin: Earth and Venus, a common kinship?	7 ± 3 ppm	43%		von Zahn et al., 1983	5%
^{4}He	Early evolution: Interior outgassing	12 (+24/-8) ppm	>60%		von Zahn et al., 1983	3%
Noble Gas Isotopic ratios						
$^{129}Xe/^{130}Xe$	Early evolution: Large atmospheric blow-off	~3	>100%			5%
$^{136}Xe/^{130}Xe$	Origin/evolution: U-Xe hypothesis	~1	>100%			5%
$^{40}Ar/^{36}Ar$	Early history: Interior outgassing	1.03 ± 0.04 or 1.19 ± 0.07	12% (average)	Pioneer Venus Venera 11/12	Hoffman et al., 1979 Istomin et al., 1980	5%
$^{36}Ar/^{38}Ar$	Late formation: Large impact	5.56 ± 0.62 or 5.08 ± 0.05	12% (average)	Pioneer Venus Venera 11/12	Donahue et al., 1986 Istomin et al., 1980	5%
$^{21}Ne/^{22}Ne$	Earth/Venus origins: Twin planet hypothesis	<0.067	>200%			5%
$^{20}Ne/^{22}Ne$	Earth/Venus origins: Twin planet hypothesis	11.8 ± 0.7	6%		Donahue, 1986	5%
$^{3}He/^{4}He$	Evolution: Impact of solar wind	$< 3 \times 10^{-4}$	>200%		Hoffman et al., 1980	10%
Light-Element Isotopic Ratios						
HDO/H_2O	Atmospheric loss, past/current volcanic activity	0.019 ± 0.006	32%			5%
$^{15}N/^{14}N$	Atmospheric loss since planetary formation	0.0037 ± 0.008	22%	PV	Hoffman et al., 1979	5%
$^{33}S/^{32}S$	Past/current volcanic activity, magmatic composition	~0.0079	>100%			5%
$^{34}S/^{32}S$	Past/current volcanic activity, magmatic composition	~0.0443	>100%			5%

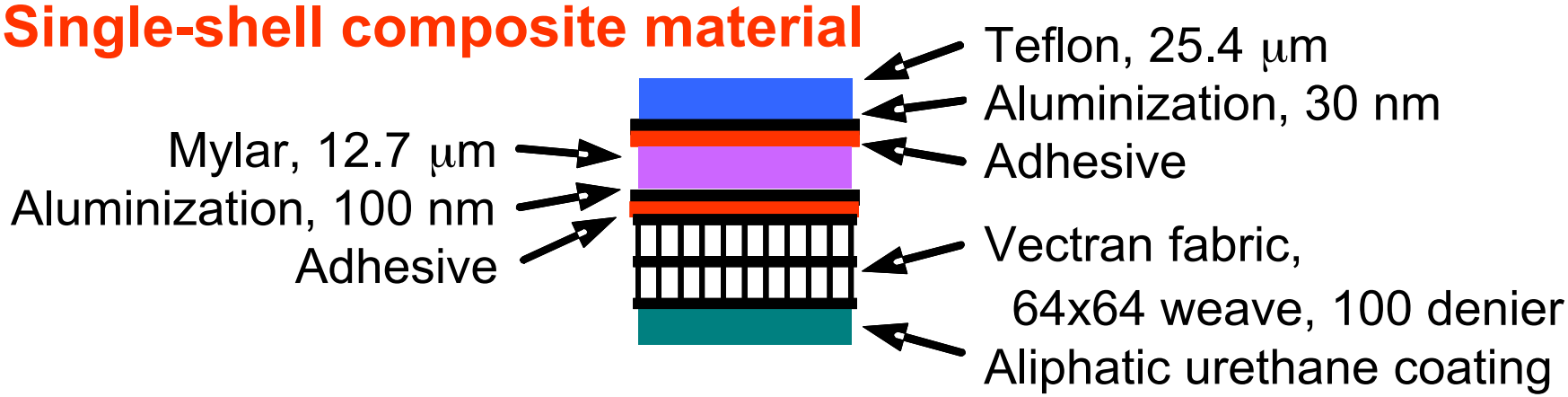
VALOR
Balloon Design Approach

- **Benign thermal environment:** **altitude 54-56 km**
- **Capable for long duration:** **superpressure (constant volume) balloon**
- **Sphere:** **most mass efficient**
- **Robust:** **safety factor (ratio of burst load to actual load) >2.5 in the most adverse combination**
- **Low gas permeability:** **metallized film**
- **Minimum day/night temperature variations:** **minimum optical absorptivity/infrared emissivity ratio (α/ε)**
- **Tolerate sulfuric acid of Venus clouds:** **fluoropolymer outside layer**

Full-Scale Prototype Balloon ("Alpha") Has Been Designed, Built and Tested by JPL/WFF/ILC Dover Team

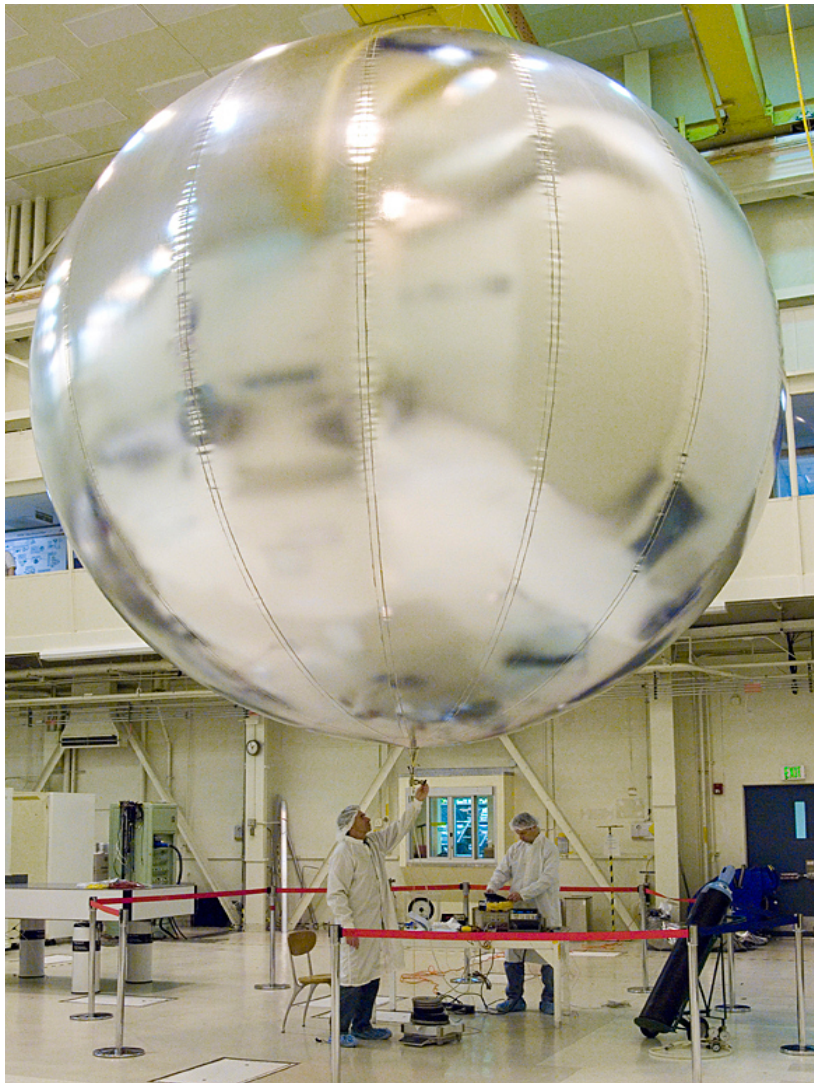
Balloon metric	Value
Diameter	5.5 m
Envelope areal density	176 g/m^2
Balloon mass	23.7 kg
Payload mass	44 kg
Helium mass	7.8 kg
Payload mass fraction	0.58

Single-shell composite material

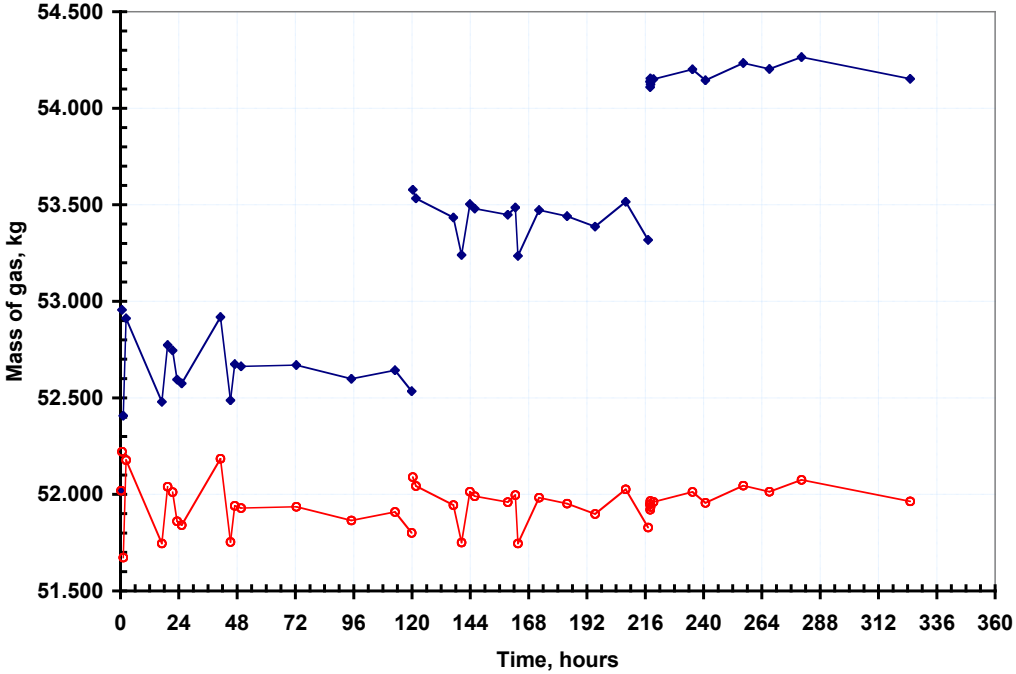


ILC Dover proprietary sulfuric acid resistant adhesive for outer layer

VALOR Prototype Balloon Tests
No Helium Leak In 2-week Test



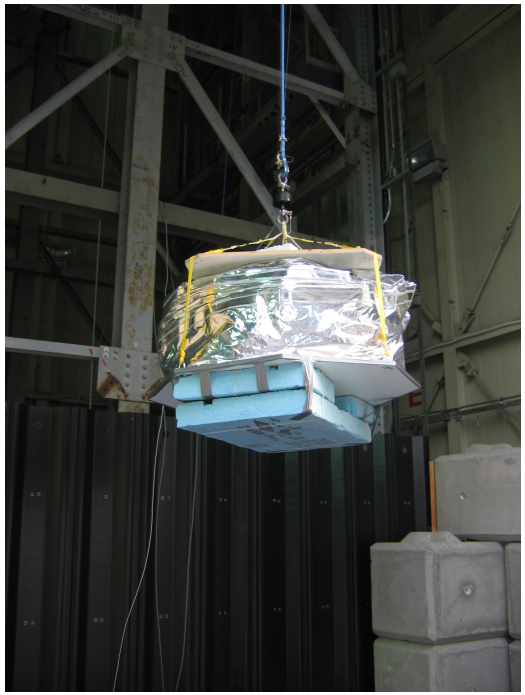
- Balloon inflated with ~50/50% helium-nitrogen in JPL SAF clean room
- Known amounts of nitrogen added two times to vary superpressure level
- Monitored buoyancy, superpressure, ambient pressure, temperature and humidity to calculate mass of gas
- No noticeable leak measured



VALOR Prototype Deployment Test

Test objectives

- Verify deployment scheme concept
- Verify balloon structural robustness to deployment shock
- Estimate time of balloon untwisting
- Measure deployment shock at parachute attachment point



Packed balloon before deployment

Balloon after deployment

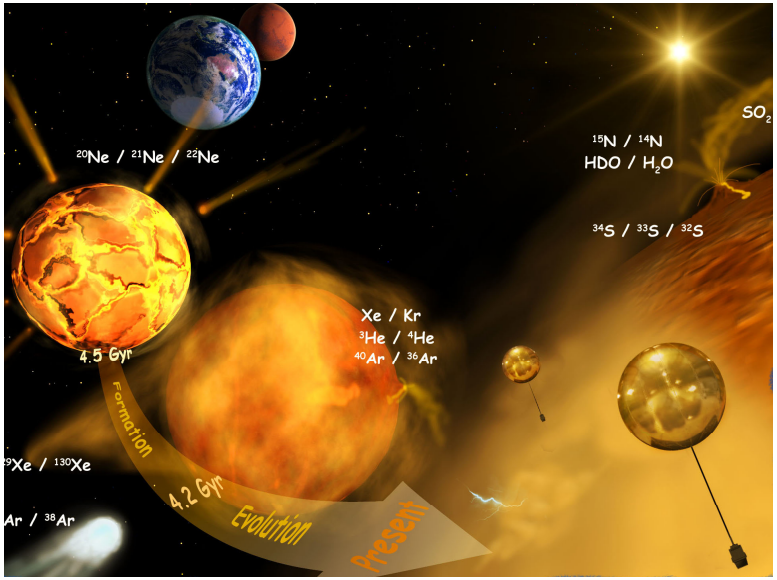
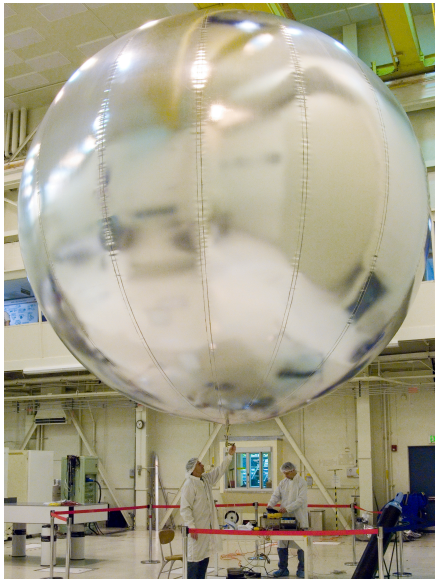
Test Results

- Balloon deployed in flight-like configuration at JPL drop-tower (bldg.280) with 37 kg attached.
- Free-fall distance was ~ 9 m
- Test was successful, no structural damages found after inspection
- Untwisting time was < 1 sec, much too short to cause a problem
- Measured shock at deployment was 1800 N, about 20% lower than expected from model prediction.

Summary

Viable Mission Architectures Exist for Discovery-Class Balloon Missions to Venus

- VEGA Balloons

- VALOR TMC Experience: No Major Weaknesses

In-Situ Exploration is the Next Step to Understand the Origin, Evolution, Chemistry, and Dynamics of of our Sister World