IN-SITU EXPLORATION OF VENUS ON A GLOBAL SCALE: DIRECT MEASUREMENTS OF ORIGINS AND EVOLUTION, METEOROLOGY, DYNAMICS, AND CHEMISTRY BY A LONG-DURATION AERIAL SCIENCE STATION

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ABSTRACT

Drifting in the strong winds of Venus under benign Earth-like temperature and pressure conditions, an instrumented balloon-borne science station presents a viable means to explore, *in-situ*, the Venusian atmosphere on a global scale. Flying over the ground at speeds exceeding 240 km/hour while floating in the Venusian skies near 55 km altitude for several weeks, such an aerostat can conduct a “world tour” of our neighboring planet, as it circumnavigates the globe multiple times during its flight from equatorial to polar latitudes. Onboard science sensors can repeatedly and directly sample gas compositions, atmospheric pressures and temperatures and cloud particle properties, giving unprecedented insight into the chemical processes occurring within the sulfuric clouds. Additionally, interferometric tracking via Earth-based radio observatories can yield windspeeds to better than 10 cm/sec over one-hour periods, providing important information for understanding the planet’s meridional circulation and enigmatic zonal super-rotation, as well as local dynamics associated with meteorological processes. As well, hundreds of Gas Chromatograph Mass Spectrometer (GCMS) spectra collected during the flight can provide measurements of noble gas compositions and their isotopes with unprecedented accuracy, thereby enabling fundamental new insights into Venus’s origin and evolution.

1. INTRODUCTION

Despite a variety of exploratory missions to Venus over four decades, including a dozen short-lived probes, two balloons, and several long-lived orbiters, our understanding of Venus is poor. Its formation, evolution, geology, global circulation, and extreme climate are outstanding scientific mysteries, all of which impact fundamentally our understanding of planets in the inner solar system, most particularly the Earth [1]. ESA’s well-instrumented Venus Express mission will provide significant new measurements from its polar orbit. This relatively low-cost yet powerful mission exploits 3-D remote sensing techniques validated by the Galileo and Cassini flybys [2,3] to peer into the depths of Venus, globally measuring the planet’s winds, trace gases, and selected surface properties. Yet, despite the wealth of images and spectra forthcoming from this next-generation orbiter, Venus Express is also unlikely to solve many of the major mysteries of our Sister Planet.

The cause of our ignorance about the nature of Venus stems predominantly from the dearth of sufficiently accurate *in-situ* measurements of (1) key trace constituents diagnostic of Venus’s origin, evolution, and present-day chemistry, and (2) critical atmospheric parameters diagnostic of meteorology, dynamics, and global circulation. In particular, the poorly constrained measurements of the heaviest noble gases, xenon and argon, and their isotopes leaves unknown the role of comets and asteroids in destroying Venus’s original atmosphere and supplying its current one. As another example, the incomplete spatial sampling provided by the previous suite of probes and short-lived (46-hour) VEGA balloons resulted in an absence of data over the entire afternoon/evening hemisphere from about noon to midnight local solar time. Meridional winds, zonal winds, atmospheric waves, convective motions, and local turbulence were all likewise unsampled over all but a few specific near-equatorial latitudes [4-9]. This lack of well-sampled *in-situ* "ground truth" dynamical data has resulted in an embarrassingly poor understanding of the nature of the planet's meteorology and, on a more global scale, the nature of any Hadley cells and processes powering Venus' super-rotating atmosphere and extreme climate.

Venus Express will indeed fill in some of the gaps, For example, this polar orbiter will expand coverage of the windfields in the deep troposphere near 50 km altitude beyond the quick sampling of the northern hemisphere obtained by the Galileo/Near Infrared Mapping Spectrometer (NIMS) [2], and will watch these winds over several Venus days to look for solar-induced circulation mechanisms. It will also scrutinize the polar dipole phenomena discovered by Pioneer Venus [10], thereby providing new insight into the nature of the polar vortices that mark the latitudinal ends of the global circulation. However, Venus Express cannot observe small-scale gravity waves – such as observed by VEGA [4, 6–8] – that may be key in transporting energy and momentum over altitude and help power global circulation. Nor can Venus Express observe meteorologically-important gas distributions nor convective or other local dynamical processes with sufficient spatial and temporal resolution to provide a clear understanding of the planet's chemically- and dynamically-coupled meteorology. As with any remote sensing mission, neither can Venus Express measure the noble gas abundances that are so critical to understanding the planet's history.

This situation can be rectified with a long-duration balloon-borne robotic expedition to Venus (Fig. 1). Drifting in the high-speed winds found in the relatively benign upper troposphere of Venus near 55 km altitude (mean temperature of 30 C at 0.5 bar pressure), such an instrumented "aerostat" can perform a month-long World Tour of Venus, circumnavigating the planet five times or more as it drifts from equatorial to polar latitudes. During its aerial sojourn, the aerostat can sample repeatedly — perhaps hundreds of times — key atmospheric properties with unprecedented precision. These include the abundances of (1) noble gases and light isotopes diagnostic of Venus' early history and evolution, and (2) numerous time- and space-varying species diagnostic of current chemical, dynamical, and meteorological processes. Tracked by Earth-based radio antennas, the aerostat can sample wave and convective phenomena critical to understanding the planet's meteorology and enigmatic zonal super-rotation. Highly-diagnostic properties that can be continuously measured include temperatures, pressures, the 3-D wind vector, and cloud particle sizes and mass densities. In addition, lightning rates and strengths can be measured electromagnetically, and nearby thunder can be quantitatively measured stereophonically.

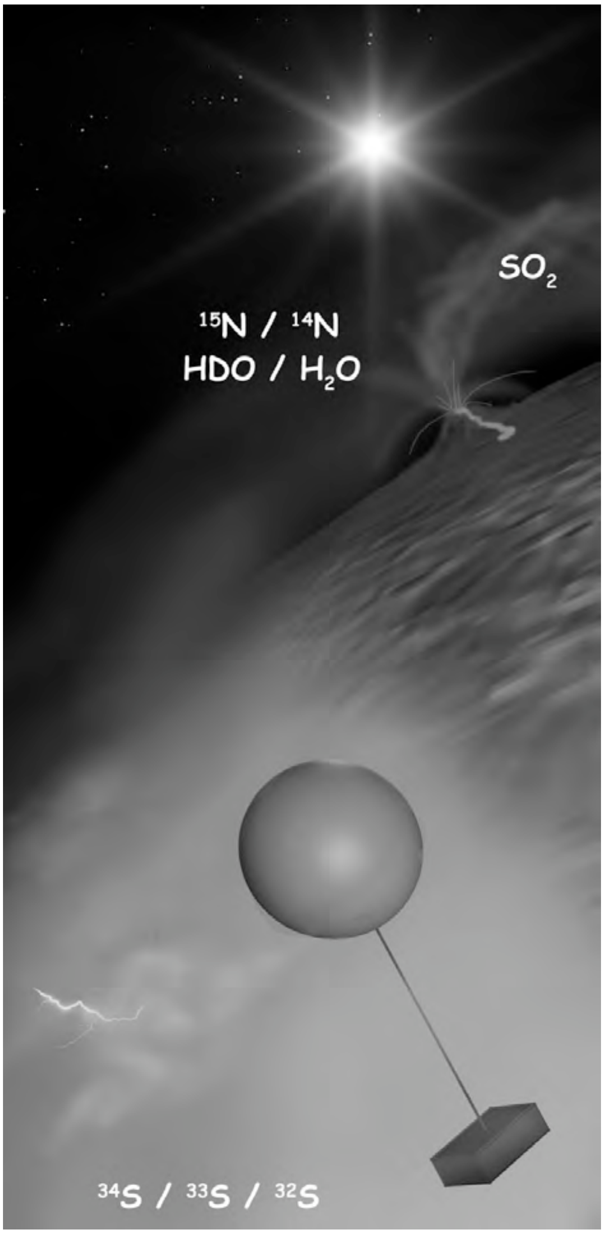

Figure 1. A lightweight, well-instrumented aerostat drifts at 240-km hour in the powerful winds of Venus, sampling and sensing tell-tale trace gases, cloud particles, lightning, and dynamics.

2. SCIENCE OBJECTIVES

The major science and measurement objectives of the Venus aerostat are outlined in Table I. As promoted by the National Research Council Decadal Study [11], primary among these objectives is a fundamental new understanding of the origin and evolution of Venus. As a first step, this requires precise knowledge of the abundances and isotopic ratios of noble gases that can only be measured *in-situ* (cf., Baines, 2005, in these Proceedings for a comprehensive description). Of particular interest is xenon, the heaviest noble gas, and its nine isotopes, none of which have been measured on Venus. Precise xenon isotopic abundances can determine the cometary contribution of volatiles, and can provide direct evidence of a global atmospheric blowoff caused by a major impact during the late stages of planetary formation.

Other noble gas isotopes, such as ^{40}Ar and ^{4}He, are radiogenic daughter products of materials decaying within the deep interior. Their abundances thus provide a direct measure of the amount of interior outgassing, key to understanding the history, extent, and style of internal geological processes and atmospheric evolution.

To understand today's climate as well as past climates, direct, localized measurements are required of a number of chemically-active species and related environmental properties. These measurements will clarify the interrelationship of a variety of active chemical, dynamical, and meteorological processes. Of particular importance are comprehensive measurements of the highly variable and dynamic middle cloud layer near 55 km altitude. Composed of sulfuric acid particles, the clouds are key drivers of Venus' thermal structure and mid-level chemistry. Galileo and Earth-based imagery has demonstrated that these clouds vary on small spatial scales [12], likely in response to variations in abundances of cloud constituents and local dynamics (perhaps self-induced), both of which are extremely difficult to measure remotely from orbit on small vertical and spatial scales.

The global circulation of Venus is perhaps even more perplexing than the localized dynamical and chemical behavior of Venus's clouds. Two worldwide dynamical phenomena are especially enigmatic: (1) the global super-rotation with powerful zonal winds at altitude exceeding sixty time the planet's rotation rate, (2) the structure of the meridional circulation, and (3) the complex dipole-shaped polar vortex observed briefly by the Pioneer Venus Orbiter (PVO) [10]. These phenomena are not understood, primarily because of the paucity of *in-situ* data revealing the three-dimensional nature of waves, eddies, and global meridional structure as sampled on small spatial and temporal scales. The Venus aerostat will make such measurements over a wide range of latitudes and spatial and temporal scales.

3. MEASUREMENT OBJECTIVES AND REQUIREMENTS

The major measurement objectives are delineated in Table II. From these follow the key instruments, experiment, and mission requirements.

Imbedded for a month within the sulfuric cloud layer at 55-km altitude, the Venus aerostat continuously explores the atmosphere *in-situ* from near-equatorial to polar latitudes (Fig. 2), thereby providing in-situ coverage at a global scale. Key measurements include (1) the abundances of heavy noble gas (e.g., Xe, Ar) and local chemically-active constituents (e.g., SO_2, OCS, H_2O) sampled with a gas chromatograph mass spectrometer (GCMS), and (2) cloud particle properties – such as mean particle radius and mass density – measured by a dual-wavelength nephelometer on the Venus Atmospheric Structure Instrument (VASI). VASI also measures the time-variability of the local pressure, temperature, and vertical wind. In addition, the aerostat acts as a wind-blown test particle for which all three components of the wind at the aerostat position can be measured by the Aerostat Radio Tracking (ART) experiment utilizing Earth-based radio interferometric and Doppler tracking observations (Fig. 3), as was performed for VEGA [4, 9, 13]. Like VEGA [4-9], the aerostat will likely experience strong vertical winds induced by convection and, perhaps, topographically-generated waves. Together, this suite of experiments provides important information for cloud formation and dissipative processes, as well as meaningful constraints on wave dynamics, turbulence, and global circulation. Additional meteorologic information is provided by (1) an electromagnetic Lightning Detector LiD) and (2) a microphone-based acoustics experiment which can measure the local rate and power of lightning flashes and its associated thunder. This *in-situ* campaign of local measurements will distinguish among a variety of proposed mechanisms responsible for the generation and maintenance of this ubiquitous cloud layer, key to understanding the current and past Venus climate.

4. MISSION DESIGN

After a 3-month cruise phase, the Pioneer-sized entry vehicle enters the Venusian atmosphere and

Table I.
Science Objectives Dictate Measurement Objectives for the Venus Aerostat Mission

Decadal Survey Cross-Cutting Themes	Aerostat Science Objectives	Measurement Objectives: Noble gas distributions	Light gas isotopes	Noble gas isotopes	Zonal and meridional winds over longitude and latitude	Global circulation constraints from trace gas spatial distribution	Sulfur cycle and other chemically active gases: H_2O	CO	OCS	H_2S	SO_2	Local dynamics: shears, variations in atmospheric structure	Cloud evolution and lightning emission rates
Origin and Evolution of Habitable Worlds	**I. Bulk Composition: Clues to the Past**												
	A. Formation: Accretion Processes	X	X	X									
	B. Evolution: Atmospheric Loss, past and present	X	X	X			X						
	C. Evolution: Interior Outgassing, past and present		X	X							X		
Processes	**II. Global Circulation**												
	A. Regional winds, small-scale waves				X	X		X					
	B. Zonal/meriidional global windfield				X								
	C. Large-scale waves				X								
	D. Polar vortices/circulation				X								
	E. Chemical tracers of latitudinal transport/Hadley					X	X	X					
Processes/ Volatiles and Organics	**III. Chemistry, Composition, and Transport**												
	A. Chemical cycles						X	X	X	X	X		
	B. Vapor tracers of vertical transport						X	X	X	X	X		
	C. Greenhouse Effect						X	X	X	X	X	X	
Processes	**IV. Middle Cloud Meteorology**												
	A. Local dynamics						X	X	X	X	X	X	X
	B. Cloud evolution		X				X	X	X	X	X	X	X
	C. Lightning characteristics												X
Origin/Volatiles/ Processes	**V. Surface/Atmosphere Interactions**												
	A. Volcanism/outgassing	X	X	X			X		X		X		

Table II.
Measurement Objectives Dictate Measurement, Instrument, and Mission Requirements for the Venus Aerostat Mission

Measurement Objective	Measurement Requirement	Instrument	Instrument/Mission Implementation Requirement
Near-Hemispheric Coverage	*In-situ* sampling over all longitudes and wide range of latitudes during mission		Mobile platform, perhaps drifting in high-speed wind field; begin ~15° away from equator to assure poleward drift
Temporal Sampling	On scales of seconds to days within a narrow latitude range (~10°), both day and nighttime sampling		Traverse both daytime and nighttime regions; sample at least for 2 days
Duration of Investigation	≥2 days for repeated sampling of waves, turbulence		Position platform in benign temperature environment near 30°C ⇒ ~55 km altitude
Observed Phenomena			
Noble gas distributions	At least once measure He, Ne, Ar, Kr, Xe to 5%	GCMS	*In-situ* sampling, span 2-150 amu
Light gas isotopes	At least once measure HDO, N, S to 5%	GCMS	*In-situ* sampling at high amu resolution
Noble gas isotopes	At least once measure ^4He, ^{40}Ar, Xe isotopes to 10%	GCMS	*In-situ* sampling, span 2-40 amu
Zonal and meridional winds over longitude and latitude	Direct sampling of latitudinal/longitudinal wind components at known pressure levels	ART	Repeatedly measure position of unpowered vehicle drifting with wind, to ~1 km (±0.4 m/s wind speeds for 1 hour drift)
		VASI	Measure pressure to ~5 mbar, during wind measurements
Global circulation constraints from trace gas spatial distribution	Measure abundances of CO and H_2O over latitude, to 5%	GCMS	Measure every 5° of latitude, at consistent Venus time-of-day
Sulfur cycle and other chemically active gases	Measure abundances of chemically-active species (*e.g.*, SO_2, H_2S, OCS, CO, H_2O,) to within 5%	GCMS	*In-situ* sampling, span 10-120 amu
Local dynamics: shears, variations in atmospheric structure	Measure variations in pressure, temperature, 3-D winds on short (<30-s) timescales	VASI	Simultaneous measurements of pressure, temperature, and vertical winds on short time scales (<240-s samples)
		ART	Doppler wind and interferometric position measurements
Cloud evolution and lightning emission rates	Measure number density and size of cloud particles simultaneously with temperature/pressure and abundances of gas constituents, measure rate and strength of lightning emissions	VASI GCMS LiD	Simultaneous nephelometer, pressure, and temperature measurements by VASI, together with simultaneous GCMS measurements of cloud constituent gases: SO_2, H_2O, OCS, and other sulfur-cycle cloud-relevant materials
Measurement Precision			
• Noble gas abundances	≤5%	GCMS	~10-minute integrations, <0.10 amu separation
• Isotopes	≤5%	GCMS	~10-minute integrations, <0.10 amu separation
• Abundances of chemically-active species	≤5%	GCMS	~5-minute integrations, <0.10 amu separation
• Pressure • Temperature • Vertical Winds • Cloud mass density • Cloud particle size	1 mbar 0.1°C 10 cm/sec 50% 50%	VASI VASI VASI, ART VASI VASI	6 sec sampling interval for fast waves/convection 6 sec sampling interval for fast waves/convection 6 sec sampling interval for fast waves/convection Dual-wavelength measurements Dual-wavelength measurements
• Radio-tracked winds • Doppler velocity	Measure position of aerostat <1 km Measure radial velocity < 10 cm/s	ART ART	Stable on-board oscillator, $\delta f/f < 10^{-10}$ VLBA

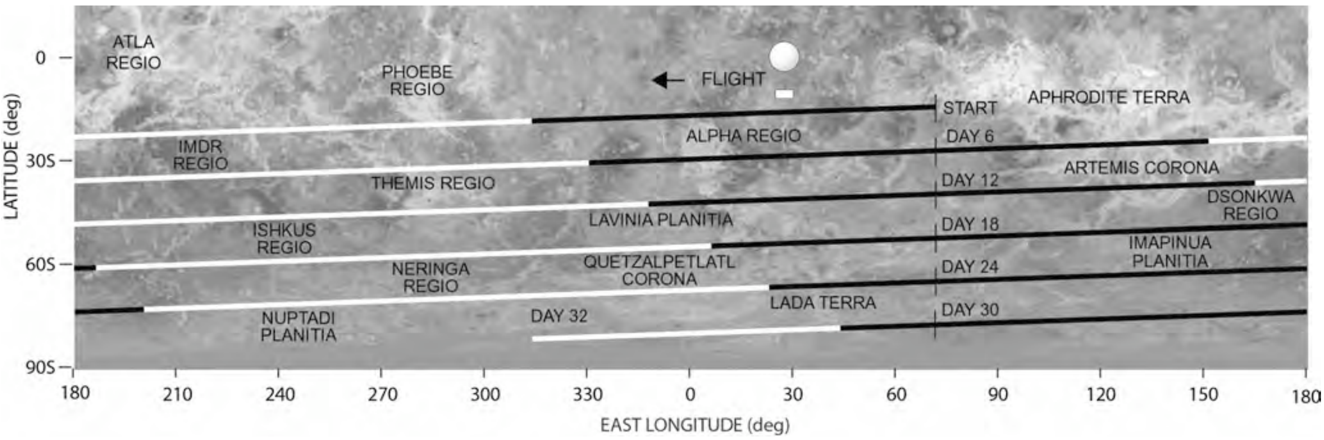

Figure 2. Flightpath of Venus Aerostat on its month-long "world tour" of Venus. Daytime and nighttime segments of the tour are depicted as white and black, respectively.

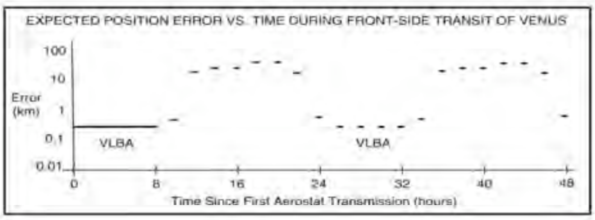

Figure 3. VLBA interfererometry can locate the aerostat with an uncertainty of just 400 meters

decelerates with a maximum g-load less than 400 g's. After a parachute descent under and deployment from its entry vehicle, the aerostat begins its flight near the east limb of Venus at about 15º N. latitude, at ~10:00 pm local time. Floating at nominal altitude of ~ 55 km in Earth-like conditions (0.5 bar, 30°C), the aerostat circles Venus ~5-6 times during its month-long reconnaissance, riding the fast zonal winds (> 240 km/hour). Due to the gentle poleward component of the winds, the aerostat traverses nearly the entire southern hemisphere, arriving near 85ºS in less than 30 days, given a mean poleward speed just half the speed measured by Galileo/NIMS [2].

The Venus aerostat uses a 5.25-m diameter spherical helium-filled superpressure balloon made of two distinct shells, each providing different functions. The outer shell is a silverized Teflon film (silver layer on the inside surface facing the inner shell) that provides sulfuric acid resistance and a low solar absorptivity (α) over infrared emissivity (ε) ratio ($\alpha/\varepsilon \sim$ 0.22). The inner shell has three layered elements. The silverized Mylar (grade C) film has a very low permeability surface for gas retention, the Vectran fabric provides tensile strength, and the polyurethane coating has a suitable adhesion surface for joining gores. A fourteen-gore construction is used for each shell. The outer shell is slightly oversized to ensure that the inner shell takes all the stress due to internal pressurization. The two layers are indexed together at five points along each meridional seam to ensure proper alignment during packaging, deployment, and inflation. The estimated mass of this balloon, including end fittings, is 19.4 kg, and the payload lift capability at the 55 km flight altitude is 40 kg. About 8 kg is used for the science payload, with another 8 kg budgeted for battery power. During the month long mission, some 6 Mbits of in-situ-sampled data is transmitted to 70-m DSN antennae on Earth. More than 100 GCMS spectra are included in this data set.

5. CONCLUSION

Long-duration *in-situ* exploration of Venus with an instrumented aerial science station (aerostat) is a viable means to understand both the history and workings of our sister planet. In addition to its outstanding science return, such an aerial vehicle funded on a Discovery-class budget would herald a new era in planetary exploration. In the not-to-distant future, aerial rovers directly descended from the Venus aerostat could be plying the skies above the treacherous landscapes and inhospitable depths of a number of worlds throughout the Solar System. Mars, the outer planets, Titan, and the hostile depths of Venus itself, all await this type of in-depth, global-scale *in-situ* coverage that only such well-instrumented aerial explorers can provide.

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