IN-SITU EXPLORATION OF THE VENUS ATMOSPHERE: KEY TO UNDERSTANDING OUR SISTER WORLD

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ABSTRACT

In-situ sampling of the Venus atmosphere is crucial for understanding the planet's complex history. A detailed inventory of diagnostic atmospheric constituents oxygen – such as the noble gases and their isotopes, and the isotopes of water, nitrogen, and oxygen – can provide fundamental new insights into the origins and early evolution of Venus and nearby planets, including the Earth. Direct sampling of sulfur-bearing compounds and chemically-related reactants as a function of altitude – from Earth-like temperature/pressure conditions in the upper troposphere to the hot (740), dense (~94 bar) conditions near the surface – uniquely clarifies the nature of a host of atmospheric dynamical, meteorological, and chemical processes and their interactive relationships with the planet's surface and geology. Finally, direct high-spatial and high-temporal resolution sampling of the planet's windfield and pressure/temperature structure provides fundamental insights into dynamical processes responsible for the planet's enigmatic super-rotating wind system.

Here, we address such key *in-situ* atmospheric science objectives, and discuss which mission classes are capable of achieving them. We then present a broad variety of potential mission architectures. Fundamental science goals are attainable by each mission class, from ~$400M Discovery-class atmospheric-sampling probe and middle-atmosphere balloon missions to flagship-class, long-duration balloon and lander missions to the planet's lower atmosphere and surface.

1. INTRODUCTION

The exploration of Venus is experiencing a renaissance as space agencies in Europe and Japan develop and launch missions to Earth's sister planet. On November 9, 2005 the European Space Agency successfully launched its Venus Express orbiter mission from Russia's Baikonur lunch complex. The spacecraft arrives at Venus in April, 2006. As a rapid-development follow-on to the Mars Express mission, Venus Express uses the Mars-Express-based bus and an array of instruments inherited from the Rosetta and Mars Express missions to provide the most systematic, thorough and complete investigation of Venus's thick atmosphere yet achieved.

During its 16-month prime science mission, nominally beginning in May 2006, the Venus Express orbiter will circle the planet daily in a polar elliptical orbit, regularly imaging and sounding the planet, from the upper atmosphere, through its various middle-level cloud layers, and down to the depths of the lower atmosphere and surface. A variety of UV, visible, near-IR, mid-IR, and radio techniques will map clouds and chemically-reactive species throughout the atmosphere down to the surface, enabling a new understanding of Venus's active photo- and thermo- chemical processes. Near-IR instruments – such as PFS, VIRTIS, and the IR-channel of SOIR – will map surface properties and search for active volcanism. The Venus Radio experiment (VeRa) will periodically acquire detailed radio occultation profiles down to the ~ 36 km level. It will also probe the surface in its bistatic radar mode, using earth-based radio telescopes to receive the echoes of VeRa signals directed at the surface. In the upper reaches of the atmosphere, a sophisticated Fields and Particles experiment – known as ASPERA - will measure the solar wind and the flux of ionized species leaving Venus, thereby elucidating the present-day rate of loss of hydrogen and other species from the planet.

In 2010, the Japan Aerospace Exploration Agency (JAXA) will launch the Venus Climate Orbiter (VCO). Its suite of four cameras will image repeatedly the planet's cloud systems at two levels and surface from an equatorial orbit. Together, Venus Express and VCO will globally map both the observed winds and theoretically-derived equilibrium wind field of Venus throughout many Venus days, thereby providing information extremely useful for determining the nature of dynamical processes powering the planet's baffling world-wide super-rotating zonal winds (cf. Section 5).

Both of these missions will provide fundamental new data on the nature of the planet's surface. In particular, near-infrared maps in the 0.9-1.2-μm range will reveal the spatial variability of thermal surface emission, as due to variations in elevation and surface composition. The adiabatic lapse rate of ~ - 8K per km altitude ensures dramatic variations of surface thermal flux with elevation, as previously demonstrated by the flyby mapping of the Near Infrared Mapping Spectrometer (NIMS) on-board the Galileo spacecraft enroute to Jupiter [1,2] and by groundbased observations [3,4]. Several useful spectral "windows" exist in the 0.9-1.2-μm range, as reported by NIMS and in shorter-wavelength observations by the Visual Infrared Mapping Spectrometer (VIMS) enroute to Saturn [5]. Venus Express and VCO will exploit these windows to map surface properties. In particular, these missions plan to spectrally map the globe at medium-spatial-resolution (~ 50 km, accounting for diffusion of upwelling radiation caused by atmospheric scattering). Incorporating known elevations from Magellan and Pioneer Venus Orbiter radar measurements in the analysis, these mission hope to separate elevation effects from effects due to variations in the emissivity of surface materials, and thus provide meaningful constraints on the distribution of surface materials over the globe [6]. As well, both missions plan to conduct searches for active volcanism, watching for unusual spatial and/or temporal anomalies in surface brightness [7]. or low-altitude abundances of volcanic gases (such as SO_2). The discovery and characterization of such active volcanism – the first for any planet beyond Earth – would provide a fundamental key to understanding the planet's geology, interior, atmospheric evolution, and climate.

Additional impetus for the new renaissance for Venus exploration comes from the American planetary science community. In 2003, under the auspices of the Space Studies Board of the National Research Council, the community's Solar System Exploration Survey (SSES) produced its report "New Frontiers in the Solar System: An Integrated Exploration Strategy" [8]. A major finding of this "Decadal Survey", as this report is informally known, is the need for direct, in-situ sampling of Venus, of both its atmosphere and surface. To this end, the SSES recommended a Venus In-Situ Exploration (VISE) mission as one of four proposed new highest priority New-Frontiers-Class (~ $ 800M) solar system missions. This mission would sample surface material in order to directly assess its composition and mineralogy, and perhaps determine its age. To allow time to perform in-depth investigation of the samples, the SSES recommended lofting the material via balloon to the relatively cool middle atmosphere near 55-km altitude, where the Earth-like conditions there would prolong the material analysis period by several days until high-speed winds blew the airborne device over the horizon as seen from Earth. Sampling of the atmosphere during this period as well as during the lander's descent would reveal abundances of inert noble gases and their isotopes, as well as inventory a wide range of reactive gases that would provide "ground truth" to the gases sounded by Venus Express and ground-based spectroscopy.

Here, we review the need for in-situ sampling of Venus, concentrating on the scientific issues and objectives that can be readily accomplished with relatively low-cost Discovery-class missions. We then expand the discussion to cover all of the high-priority Venus science objectives identified by the Decadal Survey, and summarize viable mission architectures that can accomplish each of these objectives.

2. THE NEED FOR *IN-SITU* EXPLORATION OF VENUS

More than any other pairing of terrestrial planets, Venus and Earth are virtual twins. To within 20%, they have the same radius, volume, mass, and gravity. They also have similar compositions. At the tops of their major clouds, they also have similar temperatures and pressures. Furthermore, based on a simple, first-order analysis of the solar flux and the deposition of solar energy as determined from their respective solar distances and global geometric albedos, they should have the same effective temperature.

Yet, Venus does not follow our expectations. Its mean surface temperature is nearly 2.6 times that of Earth (740 K vs Earth's 288 K mean). Despite a rate of rotation more than 100 times slower than Earth's, it's solar-powered 1-bar-level winds flow globally at an average speed greater than the sustained speed of the Earth's mightiest jet streams. Both the surface and atmosphere of Venus are exceedingly dry (~ 50 ppm, vs ~ 300,000 ppm in Earth's atmosphere). Consequently, its ubiquitous cloud system is comprised not of water, but of sulfuric acid, belying a complex cycle of sulfur-based corrosive chemistry throughout the planet's extensive 94-bar thick atmosphere and surface.

Thus, despite their bulk similarities, Venus is not at all like Earth. More than any other terrestrial planet, Venus is an alien place, seemingly inhospitable to the types of long-duration, *in-situ* exploration humans have accomplished on Earth, the Moon, Mars, and currently being planned for Mercury by ESA's Bepi Colombo mission. The strange, alien nature of Venus is linked to it history. Due to both cataclysmic and subtle events in the past, Venus proceeded along a distinctly different evolutionary path than Earth. Answering fundamental questions of Venus' history – as only can be done with *in-situ* sampling of ancient materials imbedded within the planet's atmosphere and surface – will undoubtedly reveal key lessons for the past, present, and future of Earth's environment and climate, as well as all terrestrial planets.

As noted by the Solar System Exploration Survey [8], direct sampling of atmospheric constituents is key to understanding how the planet formed and evolved as well as understanding the complex chemistry coupling the surface and atmosphere. In particular, the heavy Noble gas elements xenon, krypton, and argon and their isotopes provide an historical record of ancient events, yielding a direct accounting of planetary formation and early evolutionary processes. Due to their known rates of radioactive decay, some of these materials also provide dating constraints on geologic processes which over the eons may have delivered materials from the deep interior to the surface.

The remarkable property that renders the noble gases and their isotopes so valuable in determining ancient events is their stability against chemical alterations. Unfortunately, this stability against chemical reactions manifests itself as well in an absolute stability against photonic interactions. Thus no spectral features exist. Consequently, the abundances of these molecules cannot be readily assessed by remote sensing techniques, as from the Venus Express orbiter. Only *in-situ* sampling can do it.

Beyond sampling of noble gases for understanding the historical record, the sampling of the plethora of other constituents present in Venus's atmosphere is extremely valuable for understanding how Venus works today. Precise, simultaneous sampling of a variety of sulfur-bearing constituents and related molecules over a wide range of altitudes, latitudes, longitudes, and time can yield important insights into cloud formation/dissipation, the sulfur cycle, meteorology, and climate. Such insights can be significantly enhanced by simultaneous measurements of local dynamical processes such as local pressure and temperature, vertical and horizontal winds, and local cloud properties (*e,g.,* particle sizes and distributions), Such precise sampling at specific altitudes can only be achieved *in-situ*. Ultimately – since atmospheric sulfur is the product of volcanism – these atmospheric insights bear directly on understanding the current state of volcanic and geologic processes.

3. NOBLE GASES: THE KEY TO THE PAST

Since noble gases are thermo-chemically and photo-chemically inert, they provide a variety of keys to unlocking Venus's past history. Non-radiogenic isotopes preserve the rccord of materials that formed the planet over the aeons. In contrast, radiogenic components are the daughters of parent molecules. The relative abundances of various radiogenic isotopes then provide a variety of clocks for understanding the history of Venus. How the planet initially formed, cataclysmic events in its early history, and the nature of major geologic events throughout its evolution are examples of basic insights potentially provided through accurate sampling of noble gases and their isotopes (cf., Fig. 1).

In the Beginning: The Origin of Venus as Revealed by Neon, Xenon, Krypton and Argon

Neon Isotopic Ratios: Earth and Venus as Fraternal Twins?

On Earth, neon in the atmosphere has an isotopic composition that is mass-fractionated with respect to neon in the mantle. This suggests that neon has escaped from Earth's atmosphere. Since neon has three stable isotopes, we can tell whether neon on the Earth and on Venus are related by mass fractionation/escape processes, or whether Venus and Earth accreted their noble gases from different sources. Specifically, if the (^{22}Ne/^{20}Ne, ^{21}Ne/^{20}Ne) ratios for Venus and Earth fall on the line expected by fractionation/escape processes, it would imply they began virtually as neon twins, sharing the same source of noble gases (and perhaps other volatiles), and then evolved via escape processes to the present-day ratios. On the other hand, if the observed ratios don't both fall on the same expected fractionation/escape line, then the two planets likely began with different isotopic ratios originating from different sources of planet-building material.

Xenon and Krypton: Tracking Down Ancient Cataclysms

Xenon (Xe) is of special interest because, on both Earth and Mars, three remarkable characteristics of the xenon abundance and that of its isotopes point to major violent events in the early histories of planets in the inner Solar System. First, xenon's nine non-radiogenic isotopes are strongly mass fractionated (with a gradient of ~4%/amu) compared to any of its plausible solar system sources [9]. Second, the radiogenic isotopes of xenon are markedly depleted. Finally, the bulk abundance of xenon is also depleted, especially with respect to krypton (Kr). The strong mass fractionation of the non-radiogenic components implies that what we see today on the Earth and Mars are ragged remnants of atmospheric escape. The bulk and radiogenic component depletions add up to the "missing Xe problem." All three Xe abundance characteristics indicate a variety of cataclysmic events on both Earth and Mars late in the planetary formation process.

Important sources of radiogenic xenon are the decay of short-lived isotopes of iodine (^{129}I, half-life 15.7 Myr) and plutonium (^{244}Pu, half-life 82 Myr). Pu-fission xenon is hard to measure. However, because iodine produces a single isotope, ^{129}Xe, I-fission xenon is relatively easy. Some 7% of Earth's ^{129}Xe is from ^{129}I, while fully 50% of the ^{129}Xe in Mar's atmosphere is from ^{129}I. Yet these abundances are much less than expected for planetary atmospheres if there had been no escape. Earth, for example, retains only ~0.8% of its cosmic complement of ^{129}I-generated ^{129}Xe produced within its accreted material. In other words, since the time meteorite parent bodies first condensed, the materials that made the Earth lost 99.2% of their radiogenic ^{129}Xe. Mars has lost more than 99.9% of its ^{129}Xe. Two scenarios can be invoked to explain these depletions.

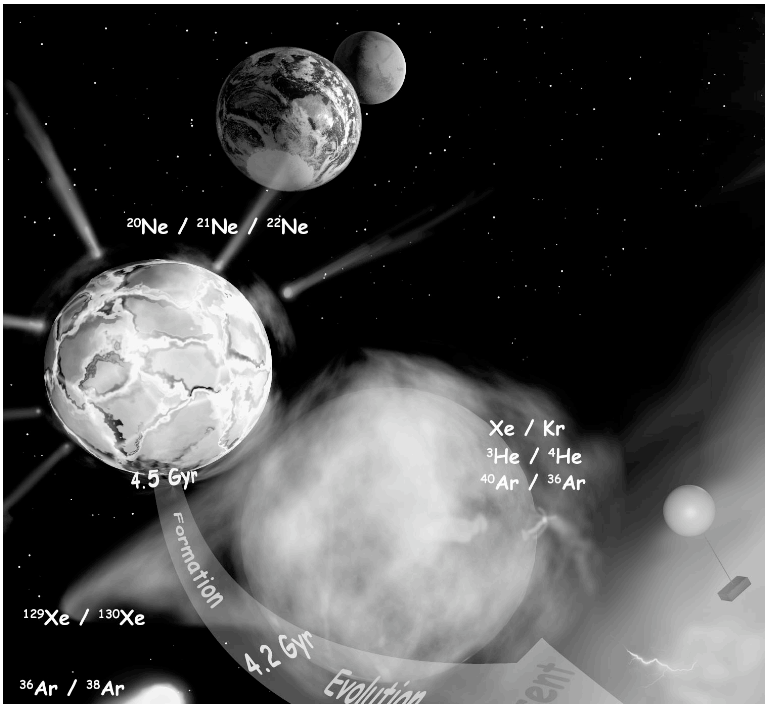


Figure 1. Clues to the formation and early history of the terrestrial planets are locked in the abundances of noble gases and their isotopes on Venus. The abundances of argon, krypton and other tell-tale tracers of Venus's past await in-situ atmospheric sampling by a future mission, such as by a probe or balloon-borne science station, depicted on the right.

In one scenario, each of the terrestrial planets experienced a major blowoff of its atmosphere, driven by hydrogen energized by solar EUV radiation more than one hundred times stronger than today. As the hydrogen escaped into space, it dragged other gases with it, especially the lighter isotopes. What remained behind became isotopically heavy [9-13]. In the Pepin model [9], escape was followed by degassing of the lighter noble gases from the interior, thus replenishing Earth's atmosphere with the amounts of lighter noble gases seen today. More evidence of a major atmospheric blowoff comes from the depleted abundances of the radiogenic isotopes of xenon observed today in Earth's atmosphere: due to radioactive decay of plutonium (Pu) and iodine (I) in the Earth's interior, these isotopes should be relatively more abundant in Earth's atmosphere. They are not, thus indicating that the blowoff occurred after the decay of Earth's plutonium in its first quarter billion years of history.

In the second scenario, the xenon isotopic pattern seen on Earth today is the signature of a common external source: either large planetesimals or comets. This hypothesis then requires that much of Earth's primordial xenon – including radiogenic products from plutonium and iodine decay – is sequestered deep in the planet's interior, Large planetesimals can fractionate isotopes by gravitational segregation [14, 15]. Comets are a possible source primarily because their compositional make-up vis-a-vis noble elements is not well-constrained. Formed in the cold reaches of the outer solar system, comets are hypothesized to incorporate xenon isotopic signatures substantially different than that expected in the inner nebula. These signatures were then delivered by comets to the Earth (and likely other nearby bodies) as the enigmatic isotopic xenon distribution seen today.

Sampling xenon and its isotopes on Venus can help resolve which mechanism is responsible for the xenon signature observed on Earth, elucidating a crucial part of Earth's early history. The solar EUV blowoff theory would be strengthened if the fractionation of xenon isotopes in Venus were found to be different than found on Earth, since the power of hydrogen blowoff is expected to vary widely between Venus and Earth. This hypothesis would be strengthened further if radiogenic ^{129}Xe were found in large amounts on Venus, rather than the small amounts (less than 7%) found on Earth, thus indicating that a blowoff took out virtually all of the iodine-generated xenon from the early terrestrial atmosphere. On the other hand, a common fractionation pattern would indicate a common source of xenon isotopes, strengthening the hypothesis that comets or large planetesimals were a major source of volatiles throughout the inner solar system. Unfortunately, no isotopic abundance information for Venus exists today. Only a crude bulk Xe abundance upper limit of <4 ppb has been assigned [16].

Additional information on the source and nature of planetary material comes from the ratios of various heavy noble gases. The uniform enhancement of xenon, krypton, and argon seen in Jupiter by the Galileo probe implies that "solar composition" planetesimals were abundant in the solar system. Kr/Xe and Ar/Kr on Venus thus provide tests on whether these solar-like planestimals also reached Venus and contributed to the volatile inventories of the terrestrial planets. However, existing measurements of krypton on Venus differ by more than an order of magnitude [17]. If the lower krypton estimate is correct, then Kr/Xe and Ar/Kr on Venus more closely resembles the solar wind and Jupiter's atmosphere, thus strengthening the solar-like planetesimal hypothesis. If the higher estimate is correct, then the Venus Ar/Kr ratio resembles not that of Jupiter but rather a number of other objects, including meteorites, Earth, Mars, and lab measurements of gases trapped in cold ice [18]. The Kr/Xe ratio then can be used to discriminate between them to provide insight into their common or dissimilar origins. Thus, a precise *in-situ* measurement of krypton is desired to help elucidate the nature of materials that originally formed the planets of the inner solar system.

Finally, isotopic measurements of Venusian xenon also provides a fundamental test of the widely-exploited "U-Xe" hypothesis for Earth [9], which asserts that terrestrial xenon is the sum of mass fractionated primordial U-Xe and a small dose of heavy isotopes obtained from the spontaneous fission of ^{244}Pu. However, U-Xe has not been detected yet elsewhere in the solar system. Furthermore, U-Xe is depleted in heavy isotopes with respect to the solar wind and other known sources, which seems implausible. Indeed, U-Xe, with a low ^{136}Xe/^{130}Xe ratio of 1.66, some 8% less than the solar wind, represents an extreme end-member of postulated fractionation patterns. The Pepin [9] U-Xe theory for Earth would be significantly bolstered if U-Xe is found to be favored in Venus.

Argon and Neon: Evidence for a Single Large Impact

A major discovery by the Pioneer Venus probes was that noble gases on Venus do not obey the "planetary" pattern generalized from Earth, Mars, and many meteorites. The striking result is that Venus has vastly too much neon and non-radiogenic argon (^{36}Ar and ^{38}Ar), indicating an unusual source of argon not seen in the other inner planets.

There are two leading theories for the high abundance of neon and argon, both involving an anomalous large impact event not experienced by the other inner planets. The first hypothesis is that the solar wind implanted noble gases into meter-size particles in the neighborhood of Venus which later assembled into a large, km-scale body that eventually hit Venus [19, 20]. Thus the source of enhanced neon and argon is the Sun, delivered via a very large, "solar-contaminated" impactor. The second scenario holds that Venus experienced an impact of a very large, very cold comet from the outer solar system. Even if this comet had the same argon-rich composition of the hypothetical pollutants of Jupiter's atmosphere, it would need to have been >200 km across to supply the enhanced argon content of Venus.

Measurement of $^{36}Ar/^{38}Ar$ in Venus' atmosphere helps to distinguish between these two large impact theories by testing whether the solar wind ratio (currently under analysis by the Genesis mission) is observed in Venus. The Pioneer Venus probes measured the $^{36}Ar/^{38}Ar$ ratio to only 10%, insufficient to confirm or deny the solar value expected by the solar-wind/planetesimal implantation hypothesis. New isotopic measurements with 5% accuracy would resolve these hypotheses.

Venus Geologic Activity Through Time: Interior Degassing Revealed by Radiogenic Argon and Helium

On Earth the most powerful probes of mantle degassing are radiogenic argon and radiogenic and nonradiogenic helium. Venus has about 25% as much atmospheric radiogenic ^{40}Ar (from potassium, ^{40}K decay, half-life 1.25 Gyr) as Earth. This strongly implies that Venus either (1) is less degassed than Earth, or (2) has significantly less potassium.

To help resolve these scenarios, helium (He) offers another probe of planetary degassing through time. ^{4}He escapes rapidly from Earth but apparently does not currently escape from Venus [16]. If there really has been no atmospheric escape, about twice as much radiogenic ^{4}He would be expected as radiogenic ^{40}Ar (assuming an Earth-like K/U ratio). What is actually observed seems to be less ^{4}He. Pioneer Venus measured ~12 ppm in the upper atmosphere, good to no better than a factor of three [17], which has been extrapolated to less than 1 ppm in the lower atmosphere [21]. If He escaped, then the corresponding ^{3}He escape flux should be larger than the ^{4}He escape rate, thus reducing the ^{3}He abundance and $^{3}He/^{4}He$ ratio. Thus, a high $^{3}He/^{4}He$ ratio in the current atmosphere would imply (1) a relatively small helium escape rate (as expected [16]), (2) a low rate of interior outgassing and (3) a relatively small amount of near surface granitic material [22].

4. BEYOND NOBLE GASES: ATMOSPHERIC LOSS AND CLIMATE THROUGH TIME

Due largely to the runaway greenhouse effect, the atmosphere of Venus today is vastly different from that at Venus' formation. The large ratio of deuterated water, HDO, relative to H_2O – some 150 times that found on Earth – attests to the loss of most of Venus' water during the planet's evolution. The hypothetical sources and mechanisms responsible for the higher D/H ratio are currently controversial and range from the loss of a primordial ocean to steady state mechanisms, wherein water supplied by cometary infall and volcanic outgassing is lost by atmospheric hydrogen escape and oxidation of Fe-bearing crustal minerals [23]. A key question is the amount of water in the past, estimated to be equivalent to a global ocean between 5 and 500 m in depth. The large uncertainty arises from a lack of precise measurements of the D/H ratio, as well as uncertainties in the current loss rate of H and O. The D/H ratio ranges from 0.013 to 0.025 based on PVO mass spectrometer and IR spectroscopy data, considering the full range of measurement uncertainties.

Additional information on atmospheric loss comes from the isotopic ratio of nitrogen $^{15}N/^{14}N$. Currently this ratio ($3.8 \pm 0.8 \times 10^{-3}$) is known to ±20%, at which precision the ratio is comparable to the terrestrial value (3.7×10^{-3}) and broadly similar to nitrogen in meteorites. However, the value is significantly different than in the atmosphere of Mars ($5.9 \pm 0.5 \times 10^{-3}$) or of Jupiter ($2.3 \pm 0.3 \times 10^{-3}$). The usual explanation is that heavy nitrogen on low-gravity Mars means that the light nitrogen preferentially escaped, while light nitrogen on Jupiter means the nitrogen was supplied there by a cometary source. If abundant argon on Venus is also attributed to comets, we then might expect that nitrogen on Venus will prove distinctly lighter than the nitrogen on the Earth which was putatively supplied by meteorites.. On the other hand, if nitrogen is heavy on Venus, significantly larger than Earth's, then atmospheric loss was a significant factor in the development of Venus. *In-situ* measurements of the isotopic ratios of $^{15}N/^{14}N$ and HDO/H_2O to 5% would provide fundamental data to understanding (1) present and past atmospheric loss rates, (2) the nature of the ancient climate of Venus, and (3) the role of comets in providing volatiles to the inner planets.

5. VENUS TODAY: UNDERSTANDING ACTIVE DYNAMICAL, CHEMICAL, AND GEOLOGIC PROCESSES

Sulfuric Gases, Water, and Their Isotopes: Tracers of Active Volcanism

In-situ measurements of SO_2 and OCS provide constraints on present-day volcanic activity and dynamical processes. Variations in atmospheric content over spatial or yearly time scales are especially intriguing. Indeed, a global decrease in SO_2 on decadal scales was first observed in the atmosphere above the clouds by the Pioneer Venus Orbiter [24]. This decrease may have been due to the dissipation of a volcanic eruption of SO_2 prior to the arrival of the spacecraft [24]. Alternatively, the SO_2 decrease may have been due to dynamical processes [25, 26]. More refined measurements, obtained *in-situ*, lower down in the atmosphere, and with more extensive spatial and temporal coverage, would provide significantly more meaningful constraints on volcanism than heretofore available.

Additional information on interior degassing during recent geologic times – primarily by volcanism – are potentially provided by the isotopic ratios of other light gases, in particular $^{33}S/^{32}S$, and $^{34}S/^{32}S$, which are fixed in volcanic and interior processes. These have had some susceptibility to modifications via surface chemistry involving iron sulfides and the atmospheric sulfur cycle. Knowledge of the sulfur isotopic ratios to 5% would help sort out the roles of recent interior degassing and processes controlling the sulfur cycle on Venus.

Another potential tracer of volcanic activity is water and its isotope HDO. Measurement of the abundances of magmatic H_2O and HDO released in a volcanic eruption would yield valuable insights into the evolution of the H_2O-poor atmosphere and the efficacy of present theories of global tectonics, insights into volcanic activity, and constraints on the oxidation rate of the crust.

Direct In-Situ Measurements of Global Circulation

Long-duration *in-situ* measurements of the Venus atmosphere, as provided, for instance, by balloon-borne instrumentation, can provide a fundamental new understanding of the global circulation of Venus. For example, direct *in-situ* measurements of winds over a wide range of latitudes and longitudes can help determine the latitudinal extent of the cloud-level Hadley cell structure, the spatial and vertical extent of planetary-scale waves, and the role of thermal tides in maintaining Venus' super-rotation. Other key phenomena that can be sampled and measured by such long-lived instrumentation include: (1) day-night environmental variations, (2) the meridional and zonal components of the super-rotating winds over latitude/longitude, and (3) the windfield within the polar vortices. Interrelationships among these are likely to be important determinants in the observed character of each. For example, the polar vortices are likely produced as natural end points for Hadley cells, while Hadley cells themselves are probably a major transporter of zonal momentum to the poles that helps maintain the superrotation of the entire atmosphere. Drifting in the winds of Venus, balloon-borne instrumentation can provide diagnostics of the atmospheric circulation that can be directly compared with theoretical predictions from general circulation models.

Global Super-rotation

The Venus atmosphere rotates up to 60 times faster at the cloud tops than the surface. This is a fundamental mystery of planetary dynamics: What torque spins the atmosphere faster than the planet itself? The key unknown here is the process by which the equatorial atmosphere is re-supplied with angular momentum lost through friction and poleward transport. The three most popular theories are:

- *Momentum transfer by waves.* Solar thermal tides, which are waves triggered by solar heating, are the main candidate for the transport of momentum in the vertical and indirectly in the horizontal (*e.g.,* the Eliassen-Palm flux), including gravity waves [27-31].
- *Convective motions from diurnal heating.* This "moving flame" model and related mechanisms [32, 33] use the phase lag of heating with depth to produce tilted convective motions that accelerate the flow.
- *Eddy coupling between meridional and zonal flows* [34-36], including eddies produced by the barotropic instability of high-latitude jets associated with Hadley circulation. In this "Gierasch mechanism," angular momentum transport occurs by a combination of mean meridional (Hadley) circulation and eddies.

The first and third mechanisms, involving the solar thermal tide and eddies, are presently the leading candidates for powering the high-speed zonal circulation. Tides have been detected in (1) the thermal IR from a record spanning roughly two-thirds of a Venus solar day [37], and (2) the day-side cloud level winds [38-40]. Unfortunately, correlated observations of thermal structure and winds on both the day and night sides, which enable the determination of the meridional heat and momentum fluxes, are lacking. Only the dayside cloud motions have been measured for more than a few days, at a sampling rate too sparse to estimate transport by waves.

Recent numerical simulations using a general circulation model (GCM) of a Venus-like atmosphere [41] have for the first time succeeded in obtaining super-rotation of the observed magnitude. The GCM indicates that a single meridional Hadley cell exists, accompanied by eddy momentum transport towards the equator throughout a height range from the surface to the cloud top. These combine to give super-rotation via the Gierasch mechanism. However, repeated observations show a strongly stable layer below the clouds that would almost certainly create multiple Hadley cells "stacked" vertically [42]. Further, this model seems to contradict observations of meridional cloud motions from a variety of flybys and orbiters – including Mariner 10 [38], Pioneer Venus [43, 44], and Galileo [1,45] – which all indicate that at the cloud tops the eddies transport angular momentum poleward, not equatorward. Thus, it is necessary to confirm that the estimates derived from the observations are correct and not an artifact of sampling bias. Such a bias in eddy momentum estimates was encountered previously in the analysis of jets observed on Jupiter [46].

Mariner, Pioneer, and Galileo investigations of the cloud level circulation on Venus indicate that at least the day-side average circulation is variable in strength [38, 42, 44, 45]. In particular, the kinetic energy of the upper atmosphere has been observed to change by 30-40%. Given the remarkable uniformity of the Venus environment – cloud cover, lack of seasons, lack of ocean-land differences, and relatively small global topographic variations – such changes in the strength of the zonal circulation are difficult to understand. Solar thermal tides and baroclinic waves are phenomena that could play a significant role, but adequate observations have not yet been obtained.

An *in-situ* balloon mission circum-navigating the planet could enable the first direct sampling of day-night variations. Relating day and night differences in meridional, zonal, and vertical windspeeds, such a mission could characterize thermal and other wave structures. Once tidal models are calibrated with such measurements, the vertical and horizontal momentum and heat transports could be determined. Based on foundations of previous work in solar thermal tidal models [28, 47, 48], analytical/numerical techniques could then be used to understand the role of thermal tides in maintaining atmospheric super-rotation.

Atmospheric Waves

Small-scale gravity waves generated by surface topography can explain large amplitude vertical winds measured by the VEGA balloons near 55-km altitude [49]. Calculations by Young *et al.* [50] indicate such waves generated near the surface can reach large amplitudes at higher altitudes, up to and above the 70-km cloud tops. Topographically forced, stationary gravity waves also best explain Magellan radio occultations [51], which measured a prominent 4-K and 2.5-km vertical wavelength gravity wave at 65 km on three consecutive orbits. Gravity waves transport momentum and therefore can play an important role in maintaining large scale circulation, including superrotation.

Building on the VEGA experience, a new balloon mission could examine gravity waves by measuring temporal and spatial variabilities in vertical velocities, pressures, and temperatures. An atmospheric structure experiment could distinguish gravity waves from convection by revealing the correlation between temperature and vertical velocity, which is in phase for convection but not for gravity waves. The power deposited at high altitudes by such waves could be obtained from the magnitude of the observed correlations.

Planetary scale waves such as Rossby and Kelvin modes have been inferred from cloud patterns in UV images of Venus (*e.g.,* [52, 53]). As noted above, these waves may help generate the mean flow zonal superrotation. Large scale three-dimensional oscillations traced by a balloon may directly reveal the presence of such large waves.

Hadley Circulation

The nature of Hadley cells on Venus is largely unknown. Whether one, two, three or even more cells exist between the equator and each pole is unknown. A long-duration *in-situ* balloon mission can measure critical aspects of the Hadley circulation in several ways. Both the meridional motion of the balloon and the latitudinal variation of the dynamically-sensitive disequilibrium species CO measured *in-situ* can be used to constrain bulk meridional motions and thus the latitudinal extent of the Hadley circulation. Additionally, latitudinal gradients in thermal structure can be used as another key diagnostic of Hadley cell structure. For example, a relatively steep latitudinal gradient would indicate the poleward edge of a cell.

Polar Vortices

At the poles, ultraviolet images from Mariner 10 and Pioneer Venus found that the circulation is organized in a pair of hemispheric vortices (see Fig. 2a). Moreover, in the middle of the northern vortex, there is a remarkable dipole feature rotating about the pole. Discovered in 11.5-µm Pioneer/VORTEX maps ([54], *cf.*, Fig. 2b,) the limited (72-day) observations feature indicateda 2.7-day rotational period, on average. However, this period varied significantly, and the entire dipolar construct nutated at times, with the rotation axis wandering 500 km from the pole in an Earth day. Large variations also occurred in the detailed structure. Usually, the bright regions had a chevron shape. Often, bright filaments connected the two features, typically crosswise.

Whether such a dipolar feature exists as well at the south pole is presently unknown. If one exists, it should be readily visible to Venus Express by the late spring of 2006. Mapping the polar regions regularly and repeatedly over its 18-month nominal mission, Venus Express will obtain detailed uv, visible, and thermal infrared maps and movies of these intriguing features.

Complementary to such regular mapping coverage, an *in-situ* long-duration balloon mission flying in the polar skies can provide detailed environmental measurements needed to gain a clear understanding of the local dynamics involved in the generation and maintenance of polar dipoles. By continuously sampling temperatures, pressures, cloud properties, and both the vertical and horizontal components of the winds, such a mission could ascertain the 3-D nature of local phenomena influencing the polar circulation.

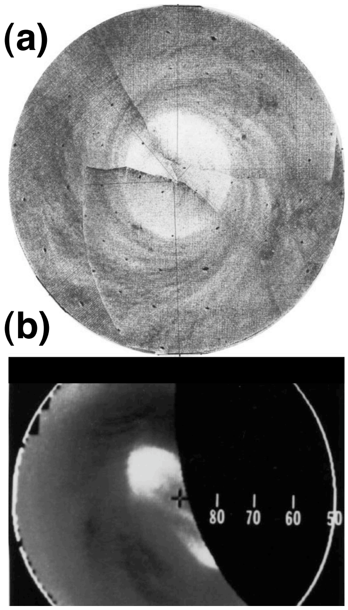


Figure 2. Circum-polar vortices: (a) Vortex organization of Venus' southern hemisphere observed from Mariner 10 in 1974 [55]. The equator is on the periphery of the picture, and dipole features in (b) are in the bright core region centered at the pole. (b) Venus north polar dipole discovered by Pioneer VORTEX at 11.5-µm [54].

<u>Chemistry, Composition, and Transport</u>

Venus atmospheric chemistry involves complex and varied chemical cycles – H_2SO_4 cloud formation from SO_2 and H_2O, CO generated by photochemistry, OCS and HCl produced by thermochemistry, and SO_2, H_2O, and HCl in volcanic gases [56]. By influencing radiative balance, these gases and clouds play a large role in establishing and maintaining the current climate, as well as give clues to possible past climates on Venus. As well, the temporal and spatial variability of SO_2 and OCS give clues to the rate of current volcanism.

Previous *in-situ* probe missions – lasting less than an hour in the atmosphere – provided sparse sampling of these important chemical constituents. The longer-lasting VEGA balloons lacked instruments capable of measuring composition. As a result, the roles of chemically-active species in maintaining radiative balance and climate, and signaling volcanic activity, are poorly understood. A long-duration *in-situ* mission, perhaps balloon-borne, can make precise compositional measurements repeatedly over a wide range of latitudes, to help resolve these important issues.

The Sulfur Cycle

Sulfur dioxide (SO_2) plays key roles in the planet's radiative balance, atmospheric chemistry, and volcanic activity. It is the third most abundant gas below the clouds, the feedstock for the global H_2SO_4 clouds, the second most important greenhouse gas, and, as noted earlier, historically the most suspected tracer of volcanic activity. In addition, SO_2 measurements provide key data for understanding the origin of the Venus runaway greenhouse effect and the potential for an anthropogenically induced runaway greenhouse on Earth.

The stability of the atmosphere is intimately intertwined with SO_2 and its role in the sulfur cycle. The existence of H_2SO_4 clouds and ultraviolet absorbing haze (suspected comprised of sulfur allatropes) are largely due to SO_2 and the sulfur cycle. As part of this process, the low abundances of H_2O and O_2 are partly due to their removal by SO_2 in the formation of H_2SO_4. The non-uniform height profile of CO is also due to sulfur chemistry. Simply put, oxidation of SO_2 is one of the most important phenomena of Venus atmosphere.

There are three main Venus sulfur cycles. First, the geologic cycle occurs at and below the surface, and is the ultimate source of atmospheric sulfur. Under the pressure-cooker environment of the hot, CO_2-laden near-surface atmosphere, OCS and H_2S gases are released from pyrite (FeS_2), particularly during active volcanism. Next, 10-40 km above the surface, the slow atmospheric cycle occurs, transforming these species into elemental and allotropic sulfur and SO_3. The latter then produces a small amount of H_2SO_4 , by combining with H_2O. The slow cycle is thought to be responsible for producing UV-absorbing elemental and allotropic S_n, the putative major UV absorber observed in Venus. In this process, OCS is converted into CO and S_n.

Finally, the fast atmospheric cycle occurs primarily above the main cloud deck, and to some extent, in the lower atmosphere, from 40 to 80 km altitude. This chemical cycle – also involving CO – utilizes photochemical as well as thermochemical reactions, and leads to the primary production of SO_2 and bulk H_2SO_4 clouds on Venus.

Comprehensive, *in-situ* measurements of SO_2, H_2O, and CO in the middle and upper atmosphere over an extended period and range of altitudes and latitudes, together with measurements of the mass density and abundances of H_2SO_4 particles, could lead to a new understanding of cloud formation and the variability of greenhouse gases. Together, these measurements and results would provide a fundamental key dataset for understanding thermal structure, radiative balance, chemistry, and climate in Venus.

CO: A Tracer of Atmospheric Transport

CO is produced by photochemistry in the upper atmosphere as well as by thermochemistry in the middle atmosphere. Previously observed spatial variations in the CO abundance appear indicative of global-scale dynamics [57]. A 35% CO enhancement north of 47°N observed by Galileo/NIMS has been attributed to concentration by the polar descending branch of an equator-to-pole cell [58]. *In-situ* measurements over a wide range of latitudes could map CO directly, providing another means to assess latitudinal and vertical circulation.

Water

Water is the third most important greenhouse gas in Venus' atmosphere, is intimately involved in forming the global H_2SO_4 clouds, and is a potential tracer of volcanism. Furthermore, the observable H_2O inventory is $\sim 10^5$ times lower than on Earth, an important clue for understanding the different evolutionary paths for the two planets.

The VORTEX experiment on Pioneer Venus detected spatial variability of the cloud-top H_2O vapor abundance [59]. On the night side, the water abundance was below the detection limit (6 ppm) and the equatorial mid-afternoon was the wettest (up to 100 ± 40 ppm vs. <6–30 ppm elsewhere). This enhancement may have been generated by vertical uplift of deeper, moister air via convection and Hadley circulation. To validate the role of water in cloud formation, search for additional evidence of volcanic activity, and refine existing theories of atmospheric evolution, *in-situ* missions should sample H_2O over a wide range of latitudes and longitudes, to an absolute abundance of 15%.

Nitrogen

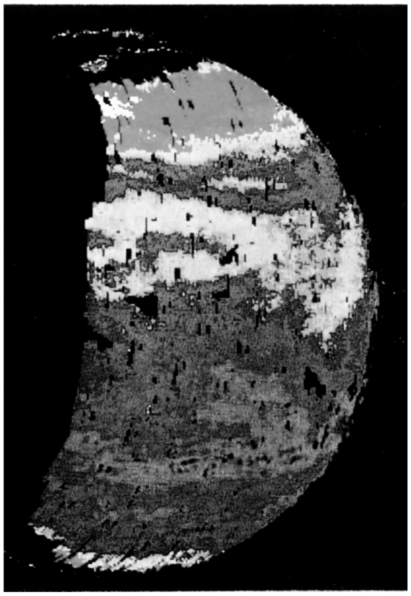
N_2 is the second most abundant species in the Venus atmosphere. Since the lifetime of N_2 on Venus is >100 Myr, a uniform mixing ratio is expected. Yet, past gas chromatograph measurements by the Pioneer Venus and Venera spacecraft are surprising, indicating a height-dependent mixing ratio. Specifically, the N_2 abundance varies widely with altitude, from a low of 2.2% (by volume) at 22 km to a high of 4.6% at 52 km. This strong altitude-dependent behavior of nitrogen implies that either the Pioneer Venus and/or Venera measurements are in error, or we do not completely understand the physico-chemical processes in the interior and atmosphere of Venus. *In-situ* measurements are needed to measure the N_2 abundance to 3% over altitude, sufficient to determine the validity of the Pioneer Venus and Venera measurements and whether N_2 is truly a well-mixed component of the Venus atmosphere

Clouds, Meteorology, and Lightning

In-situ measurements of the spatial and temporal variability of middle-level clouds and their constituent gaseous cloud-forming material can provide quantitative constraints on cloud evolution, including the growth and dissipation rates of cloud mass densities and constituent particles. The need for such measurements was highlighted by the glimpse of Venus provided by the Galileo spacecraft enroute to Jupiter.

The Near-Infrared Mapping Spectrometer (NIMS) experiment onboard Galileo found large variations in the mean particle size of cloud particles, with marked hemispherical asymmetry ([60], *cf.,* Fig. 3). Particles were ten times larger by volume in the northern hemisphere. Explanations for such marked hemispherical differences in cloud particle sizes are uncertain, but likely involve spatial variations in dynamical properties such as temperature, eddy diffusion (turbulence), and strengths of up/downdrafts that bring cloud-forming gases (principally SO_2 and H_2O) into the region. The NIMS results indicate that if cloud particle size is due to mixing of vertically stratified source regions (*e.g.,* photochemical and condensation source mechanisms), then mixing must be coherent over very large spatial scales, in turn implying relatively small variations in small-scale dynamical regimes. Yet, the distinct regional character of particle sizes may indicate sharp regional variations in the strength of dynamical mechanisms (*e.g.,* turbulence, up/downwelling). Measurements by an *in-situ* airborne mission can scrutinize cloud evolution in unprecedented detail. In particular, *in-situ* measurements of (1) cloud particle sizes, acquired simultaneously with measurements of (2) H_2O, SO_2, and other species involved in the formation of H_2SO_4 clouds, can be correlated as well with (3) the measured vertical velocities and (4) temperature variations, to distinguish among mechanisms hypothesized for the distinct regional particle-size differences seen by NIMS.

Figure 3. Near-Infrared Mapping Spectrometer (NIMS) map of hemispherical asymmetry in Venus cloud particle distribution: Light-grey-colored aerosols in the North are 10 times larger by volume than dark-colored particles in the South [60]).



Lightning – another indicator of dynamics – was detected by the Venera 11–14 landers [61, 62] and by Pioneer Venus [63, 64] as electromagnetic impulses. Venera data indicate that the rate of lightning discharges is possibly greater than on Earth [64]. Yet, only two optical investigations have successfully observed lightning [65, 66]. A long-term *in-situ* monitor of lightning within the convective cloud layer could provide key observations of lightning frequency and strength over all local times and over a wide range of latitudes.

Lightning is a potentially important source of NOx compounds (NO, NO_2 , NO_3) in the middle atmosphere, where their presence has yet to be detected. If NOx species exist at 10 ppb level or greater, they have a potentially significant impact on (a) recycling of CO_2 through NOx-HOx catalytic reactions, and (b) catalytic oxidation of SO_2 to H_2SO_4. The existence of NOx species would be indirect evidence for lightning. *In-situ* measurements of these NO-bearing species can be used to better understand middle-cloud-level chemistry and further elucidate the importance of lightning in the Venus atmosphere. The results could be compared with measurements of lightning emission rates and strengths to further clarify the role of lightning in shaping the chemistry of the Venus atmosphere.

6. *IN-SITU* EXPLORATION OF THE VENUS ATMOSPHERE: POTENTIAL MISSION ARCHITECTURES

The Decadal Survey [8] and the accompanying white paper on Venus [67] have recently specified the community-wide consensus of science priorities for Venus. Missions involving direct, *in-situ* measurements of atmospheric properties figured heavily in the recommended priorities, most notably resulting in the recommendation of a Venus atmospheric and surface sampling mission as a high-priority New Frontiers mission. Here, we briefly re-visit the Venus science objectives recommended by the Decadal Study, with an eye to identifying the minimum mission architectures that can effectively address each objective.

Tables I - III list each of the science themes, questions, and priority science investigations for Venus, as determined by the Inner Planets Panel of the Decadal Survey (cf., Table 2.1 of the Decadal Survey report [8]). Each table covers a particular Theme promoted by Decadal Study – Venus Past, Present, and Future. We have then listed, in bold, the simplest, least-expensive, mission architectures which we deem can meaningfully achieve a significant portion of these recommended priority science investigations. Both potential cost-effective orbiter and *in-situ* missions are listed. Table IV summarizes the *in-situ* mission architectures themselves. From top to bottom in Table IV, these missions become progressively more complex and costly as their capabilities in exploring the depths of Venus increase.

Fundamental science goals are attainable by each mission class, from ~$400M Discovery-class atmospheric sampling missions to Flagship-class, long-duration missions to the planet's lower atmosphere and surface. We note in particular that many high-priority science measurements and objectives appear attainable with low-cost, relatively low-risk Discovery-class mission architectures, including (1) simple probes similar to the Pioneer Venus vehicles, and (2) balloon missions building on the VEGA experience. Such missions can readily capitalize on recent improvements in sampling instrumentation, including light-weight gas chromatographs/mass spectrometers (GCMS) and precise interferometric radio and Doppler tracking of *in-situ* vehicles.

If they are to last for more than a few hours, missions to the relatively hostile lower atmosphere and surface require developments in new technologies dealing with high-temperature operations. The mean surface temperature of ~470 C requires either (1) the development of a full suite of electronic components and instruments able to work under these high-temperature conditions, or (2) the development of effective refrigeration techniques to preserve benign temperatures for the most sensitive systems, at least. An alternative scheme would be to develop air-borne technologies enabling frequent "bobbing" between the hostile lower atmosphere/surface and the relatively benign environs near 55 km altitude. This would allow rapid descents to investigate the lower atmosphere followed by quick ascents, which together limit the craft's exposure to the high-temperature environment while enabling the achievement of effective near-surface and surface science. Such developments seem possible in the next decade or so, but need strong financial support by the world's space agencies to achieve success.

Table I: Effective Mission Architectures for Discovering Venus's Past

Theme	**Questions**	**Priority Science Investigations**	**In-Situ Methods (Simplest Mission Architecture)**	**Orbiter Methods**
Past: What led to the unique character of our home planet?	a. What are the bulk compositions of the inner planets and how do they vary with distance from the Sun?	1. Determine elemental and mineralogic surface compositions	**Lander**	
		2. Measure noble gas compositions of atmospheres	**Atmospheric Probe**	
		3. Measure oxygen isotopic ratios of the unaltered surface and atmosphere.	**Lander**	
		4. Determine interior (mantle) compositions.	**Surface Stations**	Volcanic emissions via spectra?
	b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?	1. Determine horizontal and vertical variations in internal structures.	**Geophysical Network**	High-resolution Radar ?
		2. Determine the compositional variations and evolution of crusts and mantles	**Geophysical Network**	High-resolution Radar?
		3. Determine major heat-loss mechanisms and resulting changes in tectonic and volcanic styles.	**Geophysical Network**	High-resolution Radar?
		4. Determine characteristics of Fe-rich metallic cores (size, liquid and solid components).	**Geophysical Network**	
	c. What were the history and role of early impacts?	1. Determine large-impactor flux in the early solar system and calibrate the lunar impact record.	Sample Return	**Radar**
		2. Determine the global geology of the inner planets.	Low-Alt Aerostats	Radar
		3. Investigate how major impacts early in a planet's history can alter its evolution and orbital dynamics.	Geophysical Network	
	d. What is the history of water and other volatiles and how did the atmospheres of inner planets evolve?	1. Make high-precision measurements of noble gases and light stable isotopes.	**Atmospheric Probe**	
		2. Determine the composition of magmatic volatiles.	Aerostats (?), Geophysical Network	NIR spectroscopy

Table II: Effective Mission Architectures for Discovering Venus's Present

Theme	Questions	Priority Science Investigations	In-Situ Methods (Simplest Mission Architecture)	Orbiter Methods
Present: What common dynamic processes shape Earth-like planets?	a. What processes stabilize climate?	1. Determine the general circulation and dynamics of the inner planets' atmospheres.	**High-Altitude Aerostat**	Cloud tracking, Thermal Mapping
		2. Determine the composition of the atmospheres, especially trace gases and isotopes.	**High-Altitude Aerostat**	Near-IR spectroscopy
		3. Determine how sunlight, thermal radiation, and clouds drive greenhouse effects.	**High-Altitude Aerostat**	Visible, NIR, Mid-IR
		4. Determine processes and rates of surface/atmosphere interaction.	**Aerostats, Lander**	NIR, Volcanic emissions?
	b. How do active internal processes shape the atmosphere and surface environments?	1. Characterize current volcanic and/or tectonic activity and outgassing.	Aerostats ? Geophysical Network	NIR spectral imaging
		2. Determine absolute ages of surfaces.	**Sample Return**	
		3. Characterize magnetic fields and relationships to surface, atmosphere, and the interplanetary medium	Geophysical Network	Magnetospheric fields and particles expmts
	c . How do active external processes shape the atmosphere and surface environments?	1. Quantify processes in the uppermost atmospheres of the terrestrial planets.		**UV spectra, occultations, INMS**

Table III: Effective Mission Architectures for Discovering Venus's Future

Theme	Questions	Priority Science Investigations	In-Situ Methods (Simplest Mission Architecture)	Orbiter Methods
Future: What fate awaits ment and those of the other terrestrial planets?	a. What do the diverse climates of the inner planets reveal about the environment?	1. Characterize the greenhouse effect through meteorological observations.	**High-Altitude Aerostat**	Cloud/gas structure/distribution via NIR spectroscopy
	b. How do varied geologic histories enable predictions of volcanic AND tectonic activity?	1. Assess the distribution and age of volcanism on the terrestrial planets.	Low-Altitude Aerostats ? Geophys Net, Sample Return	Radar
		2. Search for evidence of volcanic gases in inner planet atmospheres.	Probe(s), Aerostat(s)	UV and NIR spectroscopy
	c. What are the consequences of impacting particles and large objects?	1. Determine the recent cratering history and current flux of impactors in the inner solar system.	Low-Altitude Aerostats Geophysical Network	Radar
	d. What are the resources of the inner solar system?	1. Assess volatile resources. 2. Assess mineral resources.	Probe(s), Aerostat(s) **Lander(s),** **Geophysical Network** **Sample Return**	NIR Spectroscopy

Table IV: Potential *In-Situ* Mission Architectures

Mission Type	**Class**	**Duration of Science Operations**	**Spatial Coverege**	**Measurement Objectives**	**Instrument Technique**
Atmospheric Probe (From 100 km to surface)	Discovery	~ 1 hour	Single point	Gas abundances Atmospheric Structure	GCMS P/T measurements Nephelometer Accelerometer
High-Altitude Aerostat (~ 57 km altitude,~20C)	Discovery	Weeks	Hemisphere	As above, plus: Meterology, dynamics circulation, volcanos	As above, plus: Radio Tracking Doppler Tracking Pressure-level Tracking
Low-Altitude Aerostat (~ 5 km altitude, ~ 440 C)	New Frontiers?	Weeks	Regional	As above, plus: Surface geology, Surface composition	As above, plus: Vis-NIR imager/spectrocopy NIR mapping spectrometer
Lander	New Frontiers	~ 3 hours	Single point	As for Probe, plus: Elemental geochemistry Surface composition	As for Probe, plus: XRD, GRS, LASAR Ablation Spectroscopy NIR mapping spectrometer Imaging microscope
Surface Station	Flagship	Weeks	Single point	As for Lander, plus: Seismometry Core sampling Surface Meteorology	As for Lander, plus: Seismometer Surface Wind Monitor
Geophysical Network (Multiple Surface Stations)	Flagship	Weeks	Near global	As for Surface Station, plus: High-Res Seismometry	Same as for Surface Station
Sample Return (Lander + Aerostat + Return Capsule)	Flagship +	~ 3 hours	Single point	As for Lander and Low-Altitude Aerostat, plus: Detailed surface mineralogy and geological and planetary evolution	Same as for Lander and Low-Altitude Aerostat

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