Experiencing Venus: Clues to the Origin, Evolution, and Chemistry of Terrestrial Planets via In-Situ Exploration of our Sister World

Kevin H. Baines[1], Sushil K. Atreya[2], Robert W. Carlson[1], David Crisp[1],
David Grinspoon[3], Christopher T. Russell[4], Gerald Schubert[5], and Kevin Zahnle[6]

We review the current state of knowledge of (1) the origin and evolution of Venus and (2) the photochemical and thermochemical processes occurring in the middle and lower atmosphere there. For each, we review the promise of on-going and planned orbital observations by ESA's Venus Express and Japan's Venus Climate Orbiter missions. We review the need for future *in-situ* measurements for understanding Venus origin and evolution and present-day chemistry, and the implications for understanding the origin and history of the Earth and other bodies in the inner solar system, as well as for understanding terrestrial planets in other solar systems. We prioritize the goals remaining in the post Venus Express era, based on the Decadal Survey (National Research Council, 2003). Using past experience with Pioneer Venus, VEGAs, Veneras, and, most recently, Venus Express as guides, we suggest appropriate techniques and measurements to address these fundamental science issues.

1. INTRODUCTION

The exploration of Venus is experiencing a renaissance as space agencies in Europe and Japan develop, launch, and execute missions to Earth's sister planet. On April 11, 2006,

[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

[2] Department of Atmospheric, Oceanic, and Space Sciences, The University of Michigan, Ann Arbor, Michigan, USA.

[3] Department of Space Sciences, Denver Museum of Nature and Science, Denver, Colorado, USA.

[4] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.

[5] Dept. of Earth and Space Sciences, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.

[6] NASA/Ames Research Center, Moffett Field, California, USA.

the Venus Express orbiter was placed into orbit about Venus by the European Space Agency. As a rapid-development follow-on to Mars Express, this relatively small (~ $300 M), fast (~ 3 years from selection to launch) mission uses the Mars-Express-based spacecraft 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 complex atmosphere yet achieved.

During its 16-month prime science mission, which began in June 2006, the Venus Express orbiter circles 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, down to the depths of the lower atmosphere and surface (c.f., Baines *et al*., 2006; Taylor, 2006; and Titov *et al*., 2006 for mission summaries). A variety of UV, visible, near-IR, mid-IR, and radio techniques map clouds and chemically-reactive species throughout the atmosphere, enabling a new understanding of Venus's active photo- and thermo-chemical processes. In addition the nadir-viewing mapping capabilities of the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) provide the potential for mapping

near-IR surface properties and a search for outgassing and thermal emissions indicative of active volcanism. The Venus Radio experiment (VeRa) periodically acquires detailed radio occultation profiles down to the ~ 36 km level. It also probes 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 Analyser of Space Plasmas and Energetic Atoms (ASPERA)—measures 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. Currently, after six months in orbit, savings in the fuel needed to maintain a stable orbit suggests that the mission is on course for a planned 16-month mission extension, with potential for a similar second extension, thus providing up to ten Venus solar days of on-orbit observations by June, 2010.

As currently planned, in that same year, 2010, the Japan Aerospace Exploration Agency (JAXA) will launch the Venus Climate Orbiter (VCO). Its suite of four cameras will repeatedly image the planet's cloud systems at two levels and surface from an equatorial orbit. Together, as currently planned, Venus Express and VCO will globally map both the observed winds and theoretically-derived equilibrium wind field of Venus throughout more than a dozen 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.

Such missions are also providing fundamental new data on the nature of the planet's surface. In particular, near-infrared maps in the 0.9–1.2-μm spectral range by VIRTIS on Venus Express are beginning to reveal in detail the spatial variability of thermal surface emission, due to variations in elevation and surface composition. As first discovered by Allen (1984) in groundbased observations and further revealed by the Galileo and Cassini flybys (Carlson *et al*., 1991; Baines *et al*., 2000), several useful spectral "windows" between CO_2 bands exist in the 0.9–1.2-μm range which allow thermal emission from Venus's hot (~ 740K) surface to be readily viewed under nighttime conditions wherein the strong glint from sunlit clouds is suppressed. 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 (Carlson *et al.,* 1991, 1993a) and by ground-based observations (Lecacheux *et al.,* 1993; Meadows and Crisp, 1996). Venus Express and VCO will exploit these windows to globally map surface properties at a spatial-resolution of ~ 50 km, as limited by the diffusion of upwelling radiation caused by atmospheric scattering. Incorporation of known elevations from Magellan and Pioneer Venus Orbiter radar measurements in the analysis is likely to enable the separation of elevation effects from effects due to variations in the emissivity of surface materials, thus providing meaningful constraints on the distribution of surface materials over the globe (Hashimoto and Sugita, 2003). In addition, both missions plan to conduct searches for active volcanism by watching for unusual spatial and/or temporal anomalies in surface brightness (Hashimoto and Imamura, 2001) or low-altitude abundances of volcanic gases (such as SO_2). The discovery and characterization of active volcanism—the first for any terrestrial planet beyond Earth—would provide a fundamental key to understanding the planet's geology, interior, atmospheric evolution, and climate, as well as provide a deeper perspective on the geologic nature of terrestrial planets throughout the universe.

Additional impetus for the new renaissance in Venus exploration has recently come from the U. S. 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" (National Research Council, 2003). 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. Despite the intense orbital scrutiny provided by Venus Express and VCO, there are major questions dealing with the evolution and chemistry of the planet, as well as its dynamics, that can only be appropriately addressed via *in-situ* measurements. These include measurements of the abundance of inert noble gases and their isotopes—which are readily accessible and bear the scars of Venus' origin and evolution—as well as a wide range of chemically-active gases important for understanding Venus' present-day meteorology and chemical cycles. None of the noble gases and just a handful of reactive gases can be measured remotely from orbiting spacecraft. Thus, as recognized by the Decadal Survey, *in-situ* atmospheric sampling is the essential next step. Many measurements can only be made by *in situ* sampling, and *in situ* sampling provides "ground truth" for the gases sounded remotely by Venus Express, VCO, and ground-based spectroscopy.

In this paper, based largely on the findings of the Decadal Survey (NRC, 2003), we review the need for *in-situ* sampling of the Venus atmosphere, concentrating on the scientific objectives that can be met by relatively small missions, such as may be affordable under NASA's Discovery Program. 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 bulk 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 also 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 288 K terrestrial mean). Despite a rate of rotation more than 100 times slower than Earth's, its 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 (~30 ppm water vs ~ 30,000 ppm in Earth's atmosphere). Its ubiquitous clouds are composed not of water, but of sulfuric acid, indicative of 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. It is an alien place, seemingly inhospitable to the types of long-duration, *in-situ* exploration thus far accomplished on Earth, the Moon and Mars. The strange, alien nature of Venus is linked to it history. Due to both cataclysmic and gradual events in the past, Venus proceeded along a distinctly different evolutionary path than Earth. Answering fundamental questions of Venus's history—as can only 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 Decadal Survey (NRC, 2003), 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 accessible historical record of ancient events, pertinent to planetary formation and early evolutionary processes. Radiogenic isotopes of helium, argon and xenon also provide dating constraints on geologic processes that 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 elements 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 dynamically related processes such as pressure and temperature, vertical and horizontal winds, and 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 either volcanism and/or tectonic activity– these atmospheric measurements bear directly on understanding the current state and recent history of volcanic and geologic processes.

3. THE EVOLUTION OF VENUS: EVIDENCE FROM
BULK PROPERTIES AND RADAR IMAGERY

The similarity of Venus and Earth in size, mass and distance from the Sun suggests that Venus and Earth had similar early histories of accretion and internal differentiation. Nevertheless, Venus and Earth proceeded along different evolutionary paths, as is evident from a comparison of the planets' satellites, magnetic fields, tectonics, rotational states, and atmospheres.

Venus does not have a moon, but the reason for this is not understood. Of course, it could simply be by chance, but Venus was likely subject to major impacts in its early evolution. Such an impact with Earth apparently produced its moon. The lack of a Venusian moon has been attributed to inward spiraling and collision with the planet of a satellite that might once have existed. It has also been explained by satellite escape. However, neither explanation is plausible. The inward spiraling scenario is unlikely since post giant impact rotation and orbital motion tend to be in the same sense, contrary to the direction of Venus's rotational spin today. The escape scenario is unlikely for reasonable Q values and moon masses (Stevenson, 2006).

Venus does not have an intrinsic magnetic field (Russell, 1980; Phillips and Russell, 1987; Donahue and Russell 1997, Nimmo, 2002), a fact that has at least two reasonable expla-

nations both connected with the planet's thermal evolution. On the assumption that Venus was initially hot and differentiated, it has long possessed a liquid metallic core. Hence it is possible that the planet had an early dynamo-generated magnetic field. Whether such a field existed and persisted for some length of time depends on the core cooling history. The rate of core cooling, controlled by the ability of the mantle to extract heat from the core, must be sufficient to support convection and dynamo action in the core. This suggests one explanation for the absence of a present day magnetic field. Venus underwent a transition during its evolution from efficient core cooling by a plate tectonic-like mode of mantle convection to an inefficient mode of stagnant or sluggish lid mantle convection that was unable to cool the core rapidly enough to support dynamo activity. Nimmo and Stevenson (2000) have proposed a similar explanation for the absence of a present day Martian magnetic field. A potential test of the existence of an ancient dynamo is the detection of remanent magnetization from this epoch. However the high surface temperature on Venus makes this detection unlikely but not necessarily impossible.

A second explanation for the lack of a magnetic field is also related to inefficient core cooling by the mantle and the lower pressure in Venus' core compared with the pressure in Earth's core due to Venus's smaller mass. It is possible that Venus's core has not yet cooled sufficiently to initiate inner core growth, but has cooled enough to prevent the operation of a purely thermally driven dynamo (Stevenson et al., 1983). It is believed that dynamo action in Earth's core is substantially facilitated by compositional convection driven by inner core solidification. The absence of plate tectonics on Venus is consistent with a style of mantle convection that is inefficient in cooling its core. That Venus might have a liquid core at present is indicated by Doppler radio tracking data of the Magellan and Pioneer Venus spacecraft which have provided an estimate of the tidal Love number k_2 (Sjogren et al., 1997). The Love number k_2 is determined from the time variations in the gravitational coefficients C_{22} and S_{22} at the solar period. Konopliv and Yoder (1996) have found $k_2 = 0.295 \pm 0.066$, a value consistent with a liquid core (Yoder, 1997).

Magellan radar global imagery strongly suggests that Venus lacks plate tectonics, a conclusion supported by the almost total absence of a global system of ridges and trenches similar to those found in the oceans on Earth (Kaula and Phillips, 1981). At the present time, Venus is a one-plate planet. Mantle convection in Venus must therefore be of the sluggish or stagnant lid mode, a relatively inefficient way to cool the core (Schubert et al. 1997). The absence of plate tectonics on Venus could have something to do with the planet's lack of water. If Venus had water early in its history

it could have had a style of mantle convection similar to plate tectonics. With a plate tectonic-like mantle convection regime there might also have been a magnetic field. It is therefore possible that atmospheric evolution, by way of an intense greenhouse effect and loss of water, had a controlling influence on the evolution of the entire solid planet, shutting down plate tectonics, core cooling, and dynamo action. The atmosphere, a relatively minor part of Venus by mass, could have controlled the thermal and rotational history of the entire planet.

The absence of plate tectonics on Venus and its implications for the relatively inefficient removal of heat from the planet's interior could account for a hypothesized major event in Venus's evolution. It has been proposed that the relatively young age of Venus's surface (about 500–800 Myr according to studies of the impact crater population, McKinnon et al. 1997, Herrick et al. 1997) was set in a global volcanic resurfacing event and that relatively little volcanism has occurred since (Schaber et al. 1992, Basilevsky et al., 1997). The resurfacing event could be the means by which Venus expels its heat. One way this could happen is by the global foundering of a thick, relatively cold and heavy lithosphere and its replacement by the relatively hot underlying mantle. Such events might have occurred episodically throughout Venus's history. Between such events the lithosphere would thicken but Venus would have no efficient way, like plate tectonics on Earth, to expel its heat. Instead the heat building up in the interior during the quiescent period would be lost in the mantle overturn when the lithosphere thickened enough to become gravitationally unstable. The initiation of such an event might be evident today on Venus's surface in the form of large coronae. McKenzie et al. (1992) and Sandwell and Schubert (1992a, b) have argued that the perimeters of several large coronae on Venus, specifically Artemis, Latona, and Eithinoa, resemble terrestrial subduction zones in both planform and topography. Artemis chasma has a radius of curvature similar to that of the South Sandwich subduction zone on the Earth. Sandwell and Schubert (1992a) proposed that the large coronae are incipient circular subduction zones. The foundering lithosphere is replaced by ascending hot mantle in a manner similar to back-arc spreading on the Earth. A consequence of a global resurfacing event would be the emplacement of mantle volatiles into the atmosphere. Of course, the resurfacing event and its consequences do not necessarily have to occur abruptly on the geologic time scale, but could take place over several hundred million years or even longer.

Although Venus is a one-plate planet at present, Magellan radar imagery has shown that there are tectonic features on its surface that resemble major tectonic features on Earth. Beta Regio, a volcanic highland, has many of the features

of a continental rift on Earth. It has a domal structure with a diameter of about 2000 km and a swell amplitude of about 2 km. It has a well defined central rift valley with a depth of 1–2 km and there is some evidence for a three-armed planform (aulacogen). Alta, Eistla, and Bell Regiones have similar rift zone characteristics (Grimm and Phillips, 1992; Senske *et al.*, 1992). Aphrodite Terra with a length of some 1500 km is reminiscent of major continental collision zones on Earth, such as the mountain belt that extends from the Alps to the Himalayas. Ishtar Terra is a region of elevated topography with a horizontal scale of 2000–3000 km. A major feature is Lakshmi Planum, which is an elevated plateau similar to Tibet with a mean elevation of about 4 km. This plateau is surrounded by linear mountain belts—Akna, Danu, Freyja, and Maxwell Montes—which reach elevations of 10 km, similar in scale and height to the Himalayas (Kaula *et al.*, 1997).

Venus rotates in a retrograde sense with a spin period of 243 days. How this spin state came about is unknown, but it might be maintained by a balance between solid body tides raised on Venus by the Sun's gravity and a frictional torque on the solid planet exerted by the super-rotating atmosphere (Gold and Soter 1969, 1979, Kundt 1977, Ingersoll and Dobrovolskis 1978, Dobrovolskis and Ingersoll 1980). Such a balance would require the source of atmospheric angular momentum to be the solar torque on the atmospheric thermal tide. Alternatively, the super-rotating atmosphere could derive its angular momentum from the solid planet, resulting in a secular variation in the planet's spin. The angular momentum of Venus' atmosphere is 1.6×10^{-3} of the solid body angular momentum, making the possibility of angular momentum exchanges, both long term and short term, highly significant for both the atmosphere and solid planet; these momentum exchanges could be manifest in measurable length of day variations (Schubert, 1983).

As noted earlier, the atmosphere of Venus bears no resemblance to Earth's atmosphere. The atmosphere of Venus is almost 100 times as massive as Earth's, with extreme surface pressure and temperature conditions: about 94 bars and 740K (Seiff 1983). Venus's atmosphere is predominantly CO_2, roughly equivalent to the amount of CO_2 tied up in carbonate rocks on Earth, and is extremely dry, with about 30 ppm of H_2O, corresponding to $\sim 10^{-3}$ of the water content of Earth's atmosphere. Consequently, Venus's ubiquitous cloud system is comprised not of water, but of sulfuric acid, indicative of a complex cycle of sulfur-based corrosive chemistry throughout the atmosphere. How did the atmosphere evolve to its present state if it was initially similar to Earth's atmosphere with a substantial complement of water? A strong possibility is that an intense greenhouse effect led to the vaporization of all water on early Venus, followed by photodissociation

of the water vapor at high altitudes and the escape of the released hydrogen into space. Without liquid water on its surface, CO_2 could then not be sequestered in the surface rocks. This change in Venus's atmosphere, if it occurred, would have triggered changes in the planet reaching all the way to its core. The loss of water would stop plate tectonics. This would have changed the style of mantle convection, slowed the rate of core cooling, and turned off the magnetic field.

If Venus once had an intrinsic magnetic field, it is possible, though perhaps not very likely, that some remanent magnetization of the crust might have survived to the present. However, while the surface temperature of Venus is below the blocking temperature of common minerals, the prolonged exposure of rocks to high temperature over hundreds of millions of years or longer would tend to destroy their magnetic domains.

How can these evolutionary story lines be checked? One way, as discussed in detail below, is the measurement of minor constituents and their isotopic compositions.

4. NOBLE GASES: THE KEY TO THE PAST

Since noble gases are thermochemically and photochemically inert, they provide a variety of keys to unlocking the history of planets, including Earth and Venus. Non-radiogenic noble gas isotopes preserve records of the materials that originally formed the planets and the evolution of their atmospheres. In contrast, radiogenic components are the daughters of parent molecules. Because noble gases are enormously depleted in planets compared to other elements, radiogenic noble gas isotopes produced by decay of even rare radioactive parents can be relatively abundant and readily measured. Consequently, the abundances of radiogenic isotopes provide a variety of clocks for understanding the formation and evolutionary history of Venus and Earth, as well as other planetary bodies such as the Moon and Mars. How these planets initially formed, the cataclysmic events in their early histories and the nature of major geologic events throughout their evolution are examples of basic insights potentially provided through accurate sampling of noble gases and their isotopes (cf., Plate 1). Accurate measurements for Venus, in particular, would help elucidate the history of the entire inner Solar System, as we now discuss.

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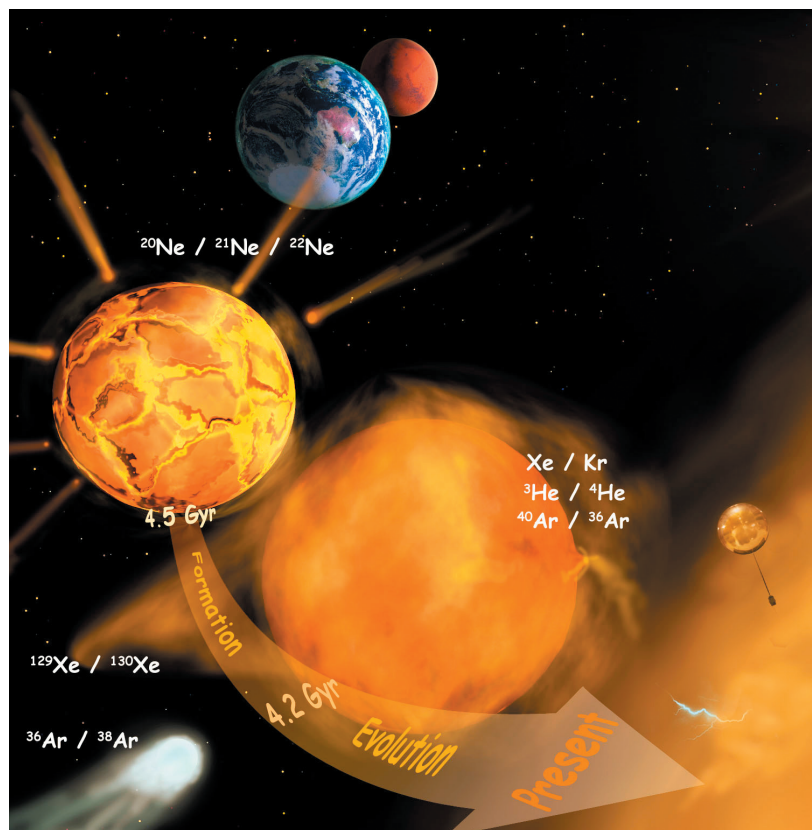
Plate 1. Clues to the formation and early history of the terrestrial planets are locked in the abundances of noble gases and their isotopes on Venus. The abundances of xenon, krypton and other tracers of Venus's past await in-situ atmospheric sampling by a future mission, such as by a probe or balloon-borne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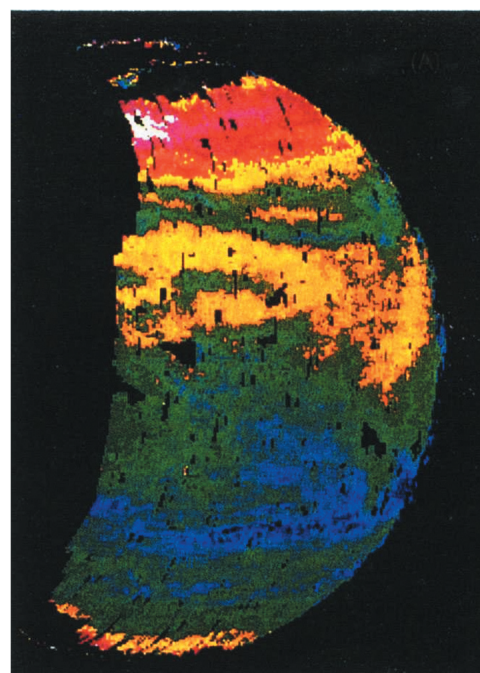

Plate 2. Near -Infrared Mapping Spectrometer (NIMS) map of hemispherical asymmetry in Venus cloud particle distribution: Light-grey-colored aerosols in the north are 10 times larger by volume than dark-colored particles in the south (Carlson et al., 1993b).

in the mantle, with the atmosphere incorporating a larger proportion of the heavier neon isotopes. This suggests that neon has escaped from Earth's atmosphere. Further evidence of neon escape comes from the ~ 100 times less neon/argon ratio seen on Earth today compared to parent nebular values. Sasaki and Nakazawa (1988) have modeled both the bulk and fractionated neon, and have shown that, in principle, Earth could lose the neon from a solar nebula composition atmosphere while generating the observed amount of fractionation.

Since neon has three stable isotopes, in principle we can tell whether neon on Earth is related to that on Venus by mass fractionation of a common ancient neon located in a common part of the parent nebula, or whether Venus and Earth accreted their neon from different sources. Specifically, if the ($^{22}Ne/^{20}Ne$, $^{21}Ne/^{20}Ne$) ratios for Venus and Earth fall on the mass fractionation line predicted by escape processes, it would imply the two planets began as neon twins, sharing the same source of noble gases (and perhaps other volatiles), and then evolved via escape to the present-day ratios. On the other hand, if the observed ratios don't both fall on the fractionation/escape line, then the two planets likely accreted their neons from disparate sources, thus indicating that a variety of formation processes and realms in the parent nebulae helped to create the inner planets. Such information has broad implications as well for the formation of extrasolar planets within other parent nebulae.

Xenon and Krypton: Coded Messages from Ancient Cataclysms. Xenon (Xe) is of special interest because, on both Earth and Mars, its abundance and isotopic composition do not closely resemble any known solar system source materials, which together point to major events in the early histories of planets. There are three major differences. First, xenon's nine non-radiogenic isotopes are strongly mass fractionated (with a gradient of ~4% per amu) compared to the solar wind or any of its plausible solar system sources (Pepin, 1991). Second, the bulk abundance of non-radiogenic xenon is depleted with respect to krypton (Kr). The depletion is a factor of ~20 when comparing Earth to typical chondritic meteorites. The strong mass fractionation of the non-radiogenic isotopes implies that what we see today on Earth and Mars are ragged remnants of atmospheric escape that occurred during the formation processes of these planets.

The third major difference involves radiogenic isotopes of xenon, which are also markedly depleted compared to the measured abundances of their radioactive parents in primitive Solar System materials. The bulk and radiogenic component depletions together add up to the "missing Xe problem." The important point is that, because xenon is the heaviest gas in the atmosphere, xenon loss implies that

escape processes affected all the gases of the atmosphere. All three xenon 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). Iodine produces just a single isotope, ^{129}Xe; thus, iodine-decay-produced xenon is relatively easy to measure. Some 7% of Earth's ^{129}Xe is from ^{129}I, while fully 50% of the ^{129}Xe in Mars'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, while Mars retains just 0.1% (Porcelli and Pepin, 2000; Ozima and Podosek, 2002). In other words, more than 99% of the ^{129}Xe produced from the radioactive decay of iodine has been lost from Earth and Mars. Given ^{129}I's 15.7 million year half-life, much of this escape must have occurred from planet–sized bodies during accretion. But, as well, its half-life is long enough that much of it must have also been lost after Earth was a planet, and some of it after the Moon-forming impact. The degree to which Venus resembles the other terrestrial planets provides a measure of the similarity of planetary evolution during the time of giant impacts in the planet formation process.

Somewhat similar arguments apply to radiogenic xenon born of spontaneous fission of ^{244}Pu. Plutonium is especially important because its 82 million year half-life probes the early evolution of the planet after accretion. Fission xenon has been detected in Earth's mantle, and there appears to be some in Earth's atmosphere. How much is uncertain, but the upper limit is about 20% of what Earth's primordial plutonium should have generated. Whatever process removed fissogenic xenon from the atmosphere (or prevented its venting into the atmosphere) was one that took place some 200 million years after Earth formed.

Four general scenarios can be invoked to explain the loss and fractionation of xenon. In one scenario, the terrestrial planets experienced different degrees of atmospheric blow-off. The cause was hydrogen escape driven by solar EUV radiation more than one hundred times stronger than today. As the hydrogen escaped, it dragged other gases with it, especially the lighter isotopes of the noble gases. What remained behind became isotopically heavy (Zahnle and Kasting, 1986; Hunten *et al.*; 1987; Sasaki and Nakazawa, 1988; Zahnle *et al.*, 1990a; Pepin, 1991). A variant attributes escape to the Moon-forming impact (Pepin, 1997). In either of Pepin's (1991, 1997) models, 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. In either model there is relatively little escape from Venus, so that Venus holds a larger and less altered portion of its original complement.

A related model ascribes most of the xenon loss to atmospheric erosion caused by impacts during accretion. Impact erosion is expected to treat all gases equally, so that the only fractionation is between gases and condensed materials. Thus one expects impact erosion to expel noble gases much more readily than water. This may have been the means by which planets lost their radiogenic xenon. But impact erosion cannot account for the mass fractionation of xenon's isotopes. Thus impact erosion is not the whole story.

In a third scenario, the xenon isotopic pattern seen on Earth today is the signature of a common external source such as large planetesimals or comets. This hypothesis then requires that much of Earth's primordial xenon—including radiogenic products from plutonium and iodine decay—be sequestered deep in the planet's interior. Large planetesimals can fractionate isotopes by gravitational segregation (Ozima and Podosek, 2002; Zahnle *et al*., 1990b). Extremely porous cold bodies immersed in nebular gases, such as large comets, are required. 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 could perhaps incorporate xenon isotopic signatures substantially different from those in the inner nebula. Such bodies could then deliver these signatures to the Earth (and likely other nearby bodies) to produce the enigmatic isotopic xenon distribution seen today.

A fourth scenario invokes properties unique to xenon among the noble gases. An example is that Xe alone among the noble gases is easier to ionize than hydrogen. Consequently, when embedded in a partially ionized hydrogen wind that is flowing upward to space, xenon tends to be present as an ion while the other noble gases are neutral. The Coulomb force between xenon ions and protons is big and thus xenon ions are relatively easily dragged away by the escaping wind, while the lighter noble gases, being neutral, go nowhere. This describes a variant on atmospheric blowoff that leaves the bulk of the atmosphere intact while allowing xenon to escape.

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. A common fractionation pattern would indicate a common source of xenon isotopes. This would strengthen the hypothesis that comets or large planetesimals were a major source of volatiles throughout the inner solar system. On the other hand, 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 might be expected to differ between Venus and Earth. The Earth-blowoff hypothesis would be strengthened further if radiogenic ^{129}Xe were found in large amounts on Venus, rather than the small amounts (~7%) found on Earth, thus indicating that a blowoff took out virtually all of the iodine-generated xenon from the early terrestrial atmosphere. Abundant radiogenic xenon on Venus would also indicate that impact erosion was relatively unimportant. Unfortunately, no isotopic abundance information for Venus exists today. Only a crude bulk Xe abundance upper limit of <4 ppb has been assigned (Donahue and Russell, 1997).

Isotopic measurements of Venus's xenon also provide a fundamental test of the "U-Xe" hypothesis for Earth, 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. The hypothetical primordial U-Xe is depleted in heavy isotopes with respect to the solar wind and other known sources. Indeed, with a low ^{136}Xe/^{130}Xe ratio of 1.66, some 8% less than the solar wind, U-Xe represents an extreme end-member of postulated fractionation patterns, and has yet to be detected in the solar system.

If U-Xe is in fact a good description of Earth's primordial xenon, then it must have come from a source that was isotopically distinct from the solar nebula as a whole. It is probable that Venus also accreted its xenon from this source. In fact, the atmosphere of Venus is perhaps the one place in the solar system where one could expect to find U-Xe, as predicted by the U-Xe hypothesis (Pepin, 1991). If it turns out that U-Xe is indeed present on Venus, as signified, in particular by a ^{136}Xe/^{130}Xe ratio about 8% lower then in the solar wind, the implications for the accretion of solid bodies throughout the inner solar system would be profound.

To resolve these various scenarios, xenon isotopic ratio measurements of at least 5% accuracy are desired. This accuracy well resolves the ~20% fractionation characteristic of terrestrial and martian xenon. To measure the difference in ^{136}Xe/^{130}Xe between xenon derived from hypothetical U-Xe and solar wind xenon (8%), or to measure abundance of radiogenic ^{129}Xe (7% on Earth), requires a somewhat higher precision, at least ~3%. Fissogenic xenon is perhaps more problematic: its reported detection in Earth's atmosphere at the 4% level is model-dependent. But in principle as much as 10% of the ^{136}Xe on Venus could be fissogenic, and a measurement accuracy of ~3% in the ^{136}Xe/^{130}Xe ratio would likely provide valuable insight.

Additional information on the source and nature of planetary material comes from the bulk 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 ("cold comets") 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 (Von Zahn *et al.,* 1983). If the lower krypton estimate is correct, then Kr/Xe and Ar/Kr on Venus more closely resemble 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 instead resembles a number of other objects, including meteorites, Earth, Mars, and lab measurements of gases trapped in cold ice (Notesco *et al.,* 2003), and the Kr/Xe ratio can then be used to discriminate between the different sources to clarify the nature and distribution of materials that formed the inner planets. Thus, determination of the bulk krypton abundance at the 5% level would provide fundamental insight into the origin of Venus, specifically providing valuable insights into the commonality of its volatile materials with other solar system objects.

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 primordial (non-radiogenic) argon (^{36}Ar and ^{38}Ar), indicating an unusual source of argon not seen in the other inner planets.

There are three leading theories for the high abundance of neon and argon, two of which involve 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 that later assembled into a large, km-scale body that eventually struck Venus (McElroy and Prather, 1981; Wetherill, 1981). Thus the source of enhanced neon and argon is the Sun, delivered via a very large, "solar-contaminated" impactor. Sasaki (1991) showed that this model can work in the more realistic context of an optically thick, vertically extended dust disk generated by collisions between planetesimals.

A second theory holds that Venus experienced an impact of a very large, very cold comet from the outer solar system. If this comet had the same argon-rich composition of the hypothetical pollutants of Jupiter's atmosphere, it would need to have been $>\sim200$ km diameter to supply the enhanced argon content of Venus. Relatively recent work by Gomes *et al.* (2005) estimates that the late bombardment delivered $\sim10^{23}$g of cometary material to Earth and Venus; i.e., the mass of a dozen 200 km diameter comets. Thus, if such cold comets existed—and enhanced noble gas abundances on Jupiter suggest that they probably did—the Gomes *et al*

(2005) result implies that there is no difficulty supplying enough argon from the outer solar system.

A third theory is that argon was captured gravitationally from the solar nebula on both Venus and Earth, but survived better on Venus because this planet's thicker atmosphere provided more protection against catastrophic loss by giant impacts (Genda and Abe, 2005).

In-situ measurement of $^{36}Ar/^{38}Ar$ in Venus' atmosphere helps to distinguish between these theories by, in particular, testing whether the solar wind ratio (currently under analysis by the Genesis mission, e.g. Grimberg *et al*., 2007) is observed on Venus. The Pioneer Venus probes measured the $^{36}Ar/^{38}Ar$ ratio on Venus to only 10%, too crude to determine if the planet's signature is that of the solar wind, based on early Genesis results. New measurements at the 1–3% level could prove valuable in separating out these scenarios once the Genesis mission results are finalized.

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 non-radiogenic helium. Venus has about 25% as much atmospheric radiogenic ^{40}Ar (from potassium, ^{40}K decay, half-life 1.3 Gyr) as Earth. This strongly implies that Venus either (1) is less degassed than Earth, or (2) has significantly less potassium (Turcotte and Schubert, 1988). A plausible scenario would be a large decrease in the degassing rate of Venus one billion years or so after formation. The low ^{40}Ar abundance coupled with the very high ^{36}Ar content results in a $^{40}Ar/^{36}Ar$ ratio near unity. In contrast, the large $^{40}Ar/^{36}Ar$ ratios measured for Earth, Mars, and Titan (~ 150–2000, Owen, 1992; Atreya *et al*., 2006a, 2006b) has been taken to indicate active geologies.

Helium (He) offers another probe of planetary degassing through time. Helium has two stable isotopes: the abundant ^{4}He and the rare ^{3}He. More than 90% of the ^{4}He on Earth is radiogenic, chiefly made by the decay of uranium and thorium (with relevant half-lives of 0.7, 4.5, and 12 billion years), whilst most of the ^{3}He on Earth is primordial (i.e., non-radiogenic). On Earth the continents, which are granitic and greatly enriched in thorium and uranium, are a major source of ^{4}He, while the mantle is a source of both isotopes in the ratio of 90,000:1. Degassing of ^{3}He indicates that Earth's interior still retains a noble gas imprint that dates to its formation. Similarly, measurements of ^{3}He and ^{4}He on Venus could give insight into the degree of mantle degassing and associated active geology there.

Helium escapes rapidly from Earth's atmosphere but apparently does not currently escape from Venus (Donahue and Russell, 1997). 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. If ^{4}He escaped, then the corresponding ^{3}He escape rate should be greater, thus reducing the ^{3}He/^{4}He ratio. On the other hand, a high ^{3}He/^{4}He ratio in the current atmosphere could imply either (1) a relatively small helium escape rate (as expected, e.g., Donahue and Russell, 1997), (2) a relatively large and relatively recent degassing event from the mantle (perhaps on the time scale of water degassing events discussed below), or (3) a relatively small amount of near-surface ^{4}He-producing granitic material (Turcotte and Schubert, 1988). Better information on both the escape rates and isotopic ratios of helium (the latter to a measurement accuracy of approximately 20%) would provide new insight into the geology, outgassing history, and evolution of Venus. The Venus Express ASPERA experiment will directly measure the helium escape rates. What remains, then, is atmospheric measurements of the helium isotopic abundances, which can only be provided by *in-situ* observations.

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

Due largely to the intense 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 (Grinspoon, 1993). 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. Another source of uncertainty is the fractionation factor between H and D loss, and how this factor has varied with time, as differing loss processes have dominated. 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. If escape fluxes are currently in the upper end of the range suggested by current (pre-Venus Express) observations, $\approx 3 \times 10^7$ cm^{-2}s^{-1}, then the greatly enhanced (over terrestrial) D/H ratio must reflect loss over the last 0.5 Gyr, and would mask a primoridal signature (Grinspoon, 1993; Donahue 1999).

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 atmospheres of Mars $(5.9 \pm 0.5 \times 10^{-3})$ or Jupiter $(2.3 \pm 0.3 \times 10^{-3})$. The usual scenario is that Earth and Mars accreted their nitrogen from a common meteoritic or chondritic source, and that heavy nitrogen on low-gravity Mars means that the light nitrogen preferentially escaped, while light nitrogen on Jupiter means that Jupiter's nitrogen was supplied by a cometary or nebular source. Because Venus has roughly the same amount of nitrogen as Earth, the expectation is that Venus accreted its nitrogen from the same common source that Earth and Mars did. Comparison of the nitrogen isotopes between Venus and Earth should help determine whether nitrogen escape was significant on at least one of the two planets. In summary, *in-situ* measurements of the isotopic ratios of ^{15}N/^{14}N and HDO/H_2O to ~3% would provide data fundamental 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.

Among the light gases, the most important to understand from the perspective of planetary composition and accretion are the stable oxygen isotopes. Because there are three such isotopes, it is possible to distinguish fundamentally different compositions from mere isotopic fractionation. For example, the Earth and Moon share the same distinctive oxygen composition, which is is clearly distinct from those of nearly all meteorites, including the meteorites that come to us from Mars and Vesta (e.g., Stevenson, 2005). Specifically, the ^{17}O/^{16}O ratio of Vestan meteorites lies about 0.02% below the Earth-Moon mass-dependent fractionation line, and Mars lies 0.04% above that line. That the Earth and Moon share the same oxygen isotopes is currently viewed as a profound mystery, because according to the best available simulations of the Moon-forming impact, the Moon forms almost wholly from the planet that struck the Earth (Canup, 2004), and hence ought to be as different from Earth as Mars is.

Similar isotopic measurements of oxygen for Venus would be valuable in understanding the relationships of the materials comprising Earth, Moon, and Venus. If Venus is distinct from the Earth and Moon, we would learn that Venus accreted from a different pool of planetesimals than the Earth did. If it is the same as Earth, it would not only show Venus accreted from the same reservoir of materials as Earth, but it would also suggest that the equivalence of the Earth and Moon is not so mysterious.

To be useful, ^{17}O/^{16}O ratios need to be measured to significantly better than 0.01%. This level of precision may be

available with tunable laser spectroscopy techniques (e.g., Christensen *et al*., 2007a, 2007b) applied to isotopic carbon-dioxide. Adequate vertical sampling would be desired to effectively address issues arising from photochemical fractionations produced by atmospheric photochemistry.

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

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Tracers of Active Volcanism

In-situ measurements of SO_2 and OCS provide constraints on present-day volcanic activity and geologic processes. Temporal variations in atmospheric content are especially intriguing. Indeed, a global decrease in SO_2 on a decadal scale was first observed in the atmosphere above the clouds by the Pioneer Venus Orbiter (Esposito, 1984). This decrease may have been due to the dissipation of a volcanic eruption of SO_2 prior to the arrival of the spacecraft (*ibid*). Alternatively, the SO_2 decrease may have been due to dynamical processes, including decadal-scale variations in the circulation within the Venus mesosphere where both SO_2 and CO exhibit steep vertical gradients (Clancy and Muhleman, 1991; Bézard *et al*., 1993). More refined measurements of SO_2, CO, and OCS 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 previously 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. However, sulfur isotopes are susceptible to modifications via surface chemistry involving iron sulfides and via the atmospheric sulfur cycle, including fractionation processes involving photochemistry. Indeed, Laboratory experiments at 193 nm obtain anomalous fractionations—deviations from simple mass-dependent fractionation—as large as 7% (Farquhar *et al.* 2004). But in practice natural samples that have not been biologically fractionated show conventional fractionations smaller than 1% and anomalous fractionations of a few tenths of a percent at most. The biggest anomalous fractionation reported in a Martian meteorite is 0.1% (Farquhar *et al*., 2007).

Useful measurements of the $^{34}S/^{32}S$ and $^{33}S/^{32}S$ isotopes ratios occur about the 1% level, which would yield quantitative constraints on anomalous isotopic effects in photochemical hot spots. More realistically, 0.1% precision is needed to discriminate reaction pathways. A long-duration mobile mission (e.g. a balloon) utilizing the high-precision afforded

by tunable laser spectroscopy (e.g., Christensen *et al.,* 2007a, 2007b) would be especially useful since good characterization of sulfur isotopes requires multiple samples obtained in many environments.

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 help to distinguish recent volcanic sources from exogenic or primordial sources, thus yielding valuable insights into the evolution of the H_2O-poor atmosphere and the efficacy of present theories of global tectonics, insights into the history and current rate of volcanic activity, and constraints on the oxidation rate of the crust.

Chemistry, Composition, and Transport

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 (Prinn and Fegley, 1987). By influencing radiative balance, these gases and clouds play a large role in establishing and maintaining the current climate. As well, the temporal and spatial variability of SO_2 and OCS give clues to the current rate of volcanic outgassing and the state of geologic activity on the planet. In addition, a fuller understanding of the radiative roles of these molecules and their connection with current and past resurfacing and outgassing would provide important clues to possible past climates on Venus.

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 their connection to volcanic activity, are poorly understood. A long-duration *in-situ* mission, perhaps balloon-borne, can make precise compositional measurements repeatedly over a range of altitudes and 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 surface-atmosphere interactions (cf., Prinn and Fegley,1987; Moroz *et al*., 1990) . 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, by constraining models of climate evolution, SO_2 measurements provide key data for understanding the origin of the Venus greenhouse effect, with implications for understanding the future climate evolution of Earth.

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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 to be comprised of sulfur allotropes) 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 in the 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 on 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 on 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 (Collard *et al.*, 1993). 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 (Taylor, 1995). *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 ~10^5 times lower than on Earth, an important clue for understanding the different evolutionary paths of the two planets.

The VORTEX experiment on Pioneer Venus detected spatial variability of the cloud-top H_2O vapor abundance (Schofield *et al.*, 1982). 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 accuracy 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, suggesting a height-dependent mixing ratio. Specifically, the N_2 abundance varies widely with altitude, from a low of 2.5% abundance near 22 km to a high of 4.6% at 52 km (e.g., Table V of von Zahn *et al.*, 1983). This apparently 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 5% 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 (Carlson *et al.,* 1993b; cf*.,* Plate. 2). 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.

Lightning—both an indicator of dynamics and an enabler of non-local thermodynamic equilibrium—was detected by the Venera 11–14 landers (Ksanfomaliti, 1979, 1983) and by Pioneer Venus (Taylor *et al*., 1979; Russell, 1991) as electromagnetic impulses. Venera data indicate that the rate of lightning discharges is possibly greater than on Earth (Russell, 1991). The locations of the flashes of the two optical investigations to have successfully observed lightning (Krasnopolsky, 1983; Hansell *et al*., 1995) are shown in Figure 1. Both plasma wave and optical observations show frequent occurrence in the dusk terminator region and on the
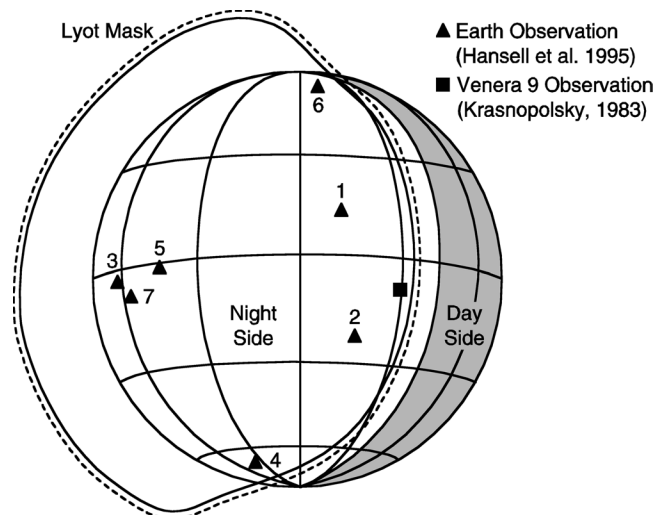

Figure 1. Locations of visible lightning flashes seen from a terrestrial telescope by Hansell et al. (1995) and from orbit by Krasnopolsky (1983).

equator similar to the local time and latitudinal asymmetries in the distribution on Earth. 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 and elucidate its role in the chemistry of the Venus atmosphere. Lightning is a potentially important source of NOx compounds (NO, NO_2, NO_3) in the middle atmosphere. The existence of NOx species is indirect evidence for lightning, as it is the only source of NO in the lower atmosphere. If NOx species exist at a level of 10 ppb 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. Krasnopolsky (2006) has recently reported an NO abundance of 5.5 ± 1.5 ppb from high-resolution spectra at 5.3 μm obtained with the TEXES spectrograph at the NASA/IRTF facility on Mauna Kea, Hawaii. The results correspond to a global flash rate of 87 s^{-1} and 6 km^{-2} y^{-1}, if the flash energy on Venus is similar to that on Earth (~ 10^9 J).

In-situ measurements of 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.

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

The Decadal Survey (NRC, 2003) and the accompanying white paper on Venus (Crisp *et al.,* 2002) have 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 Survey, with an eye to identifying the minimum mission architectures that can effectively address each objective.

Tables 1–3 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 (NRC, 2003). Each table covers a particular Theme promoted by Decadal Survey—Venus Past, Present, and Future. We have then listed, in bold, the simplest, least-expensive, *in-situ* mission architectures which we deem can meaningfully achieve a significant portion of these recommended priority science investigations. Both

Table 1. 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 2. Measure noble gas compositions of atmospheres 3. Measure oxygen isotopic ratios of the unaltered surface and atmosphere. 4. Determine interior (mantle) compositions.	**Lander** **Atmospheric Probe Lander** **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. 2. Determine the compositional variations and evolution of crusts and mantles 3. Determine major heat-loss mechanisms and resulting changes in tectonic and volcanic styles. 4. Determine characteristics of Fe-rich metallic cores (size, liquid and solid components).	**Geophysical Network** **Geophysical Network** **Geophysical Network** **Geophysical Network**	High-resolution Radar? High-resolution Radar? High-resolution Radar?
	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. 2. Determine the global geology of the inner planets. 3. Investigate how major impacts early in a planet's history can alter its evolution and orbital dynamics.	Sample Return Low-Alt Aerostats Geophysical Network	Radar Radar
	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. 2. Determine the composition of magmatic volatiles.	**Atmospheric Probe** Aerostats, Geophysical Network	NIR spectroscopy (?)

potential cost-effective orbiter and *in-situ* missions are listed. Table 4 summarizes the *in-situ* mission architectures themselves. From top to bottom in Table 4, 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 ~$450M Discovery-class atmospheric sampling missions to ~$2000M 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 tunable laser spectrometers—and precise interferometric radio and Doppler tracking of *in-situ* vehicles, to provide effective exploration of Venus at relatively low cost and low risk.

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-temper-ature 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 technological developments seem possible in the next decade or so, but need strong financial support by the world's space agencies to achieve success.

Among the major questions about Venus listed in Tables 1–3 are ones relating to the planet's interior. Clearly, we need to do more than just explore the atmosphere if we are to understand Venus and how it evolved to its present state. A possible source of information about the interior structure of Venus would be the variations that might exist in Venus' length of day or pole position. We have already

Table 2. Effective Mission Architectures for Discovering Venus's Present

Theme	Questions	Priority Science Investigations	In-Situ Methods (Simplist 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. 2. Determine the composition of the atmospheres, especially trace gases and isotopes. 3. Determine how sunlight, thermal radiation, and clouds drive greenhouse effects. 4. Determine processes and rates of surface/ atmosphere interaction.	**High-Altitude Aerostat** **High-Altitude Aerostat** **High-Altitude Aerostat** **Aerostats, Lander**	Cloud tracking, Thermal Mapping Near-IR spectroscopy Visible, NIR, Mid-IR 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. 2. Determine absolute ages of surfaces. 3. Characterize magnetic fields and relationships to surface, atmosphere, and the interplanetary medium	Aerostats? Geophysical Net. **Sample Return** Geophysical Net.	NIR spectral imaging 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 3. Effective Mission Architectures for Discovering Venus's Future

Theme	Questions	Priority Science Investigations	In-Situ Methods (Simplist Mission Architecture)	Orbiter Methods
Future: What fate awaits Earth's environment 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. 2. Search for evidence of volcanic gases in inner planet atmospheres.	Low-Altitude Aerostats? Geophys Net, Sample Return **Probe(s)**, Aerostat(s)	Radar 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 Net. Sample Return**	NIR spectroscopy (?)

noted that length of day variations on Venus are likely due to atmosphere-solid body interactions and possibly interior processes. Whereas length of day variations on Earth are of order milliseconds, length of day variations on Venus could be of order hours (Schubert, 1983). Length of day variations on Venus are potentially observable from Earth through long term radio interferometric measurements.

The size and physical state of the core, the locations and nature of mantle phase transitions, and the thickness of the crust could be determined by a seismic/geodetic network that could directly probe the interior. Knowledge of the physical state of the core, in particular whether Venus has a solid inner core, would enable understanding of why Venus does not have an intrinsic magnetic field and how dynamos

Table 4. Potential *In-Situ* Mission Architectures

Mission Type	Class	Duration of Science Operations	Spatial Coverage	Measurement Objectives	Instrument Technique
Atmospheric Probe (From 100 km to surface)	Discovery	~ 1 hour	Single point	Gas abundances Atmospheric Structure	GCMS, Tunable Laser Spectroscopy P/T measurements Nephelometer Accelerometer
High-Altitude Aerostat (~ 56 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/spectroscopy, 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 poin	As for Lander and Low-Altitude Aerostat, plus: Detailed surface mineralogy and geological and planetary evolution	Same as for Lander and Low-Altitude Aerostat

work. A geophysical network could provide measurements of the surface heat flow, an important indicator of the thermal state of the interior and the planet's complement of radiogenic elements. More information about the variations in composition and mineralogy of the surface rocks by remote sensing or *in situ* sampling or sample return to Earth or an orbiting spacecraft laboratory would clarify how differentiation has produced the Venusian crust and if there are fundamental compositional differences between the crusts of the volcanic and plateau highlands similar to the differences between oceanic and continental crusts on Earth. Finally, the radiogenic element content of surface rocks provides important constraints on Venus' thermal state and evolution.

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Kevin H. Baines, Jet Propulsion Laboratory, California Institute of Technology, M/S 183-601, 4800 Oak Grove Drive, Pasadena, California 91109, Ph: (818) 354-0481, FAX: (818) 393-5148, Email: kbaines@aloha.jpl.nasa.gov.